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Mineral resources: Geological scarcity, market price trends, and future generations

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ABSTRACT

The extractable ores of the world's geologically scarcest mineral resources (e.g. antimony, molybdenum and zinc) may be exhausted within several decades to a century, if their extraction continues to increase. This paper explores the likelihood that these scarce mineral resources can be conserved in time for future generations without intervening but instead simply relying on the price mechanism of the free market system. First we discuss the role of geological scarcity in the long-term price development of mineral resources. Then, to see whether geological scarcity affects the price of minerals we compare the historical trends in the prices of geologically scarce mineral resources with those of geologically more abundant mineral resources. The results show that in the period 1900–2013 the price mechanism did not result in high prices that provide advance warning of exhaustion of minerals. We therefore argue that if conservation is left to market forces, it is not certain that geologically scarce minerals will be timely, automatically, and sufficiently conserved for future generations. We recommend preparing international policy measures targeted at a price increase of the scarcest mineral resources, in order to accelerate substitution and recycling of these materials and help save the geologically scarcest mineral resources for future generations.

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1. Introduction

Achieving sustainable development is a central goal of the United Nations. It is the main issue in a number of agreements, conventions, and declarations, such as the Stockholm Convention (1972), the Rio Declaration (Agenda 21, 1992), the Rio+20 Declaration (The Future We Want, 2012), and the UN Report on the implementation of Agenda 21 (United Nations, 2014). In the latter document, the Sustainable Development Goal 12 is: “Ensure sustainable consumption and production patterns” and sub-goal 12.2 is: “By 2030, achieve the sustainable management and efficient use of natural resources”.

The leading definition of sustainability was formulated in 1987 by the Brundtland Commission in its report *Our Common Future*: “Sustainable development is the kind of development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987). There is debate on the interpretation of the Brundtland definition of sustainable development

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in the context of use of resources. According to Johnston et al. (2007), in 2007 there were some 300 interpretations. Two main lines of interpretation can be distinguished: (a) the “weak sustainability” interpretation and (b) the “strong sustainability” interpretation. Adherents to the “weak sustainability” interpretation argue that future generations should not have fewer consumption opportunities than the current generation and that natural resources may be exhausted on condition that they are replaced adequately by equivalent substitutes and human-made capital. However, adherents to the “strong sustainability” concept argue that the current generation should not deprive future generations from using natural resources. The concepts of weak and strong sustainability are discussed further in Baumgärtner and Quaas (2010), Johnston et al. (2007), Goodland (1995), Hansson (2010), Ayres et al. (2001), van den Bergh (2010), and White (2013).

The argumentation behind the “weak sustainability” concept is that the current generation needs commodities today in order to construct a society that improves the living conditions for current and future generations. From this point of view, exhaustion of mineral resources is not necessarily bad for future generations and their welfare does not necessarily decline as a result of exhaustion, particularly if the resources are used for investment in human-made capital. Supporters of the “strong sustainability” concept tend to be more cautious about exhaustion of resources. They argue

Table 1
The “sustainable use of resources” principle and the “inter-generational equity” principle in international conventions and agreements.

Normative principle	Included in
Sustainable use of resources	<ul style="list-style-type: none"> – 1958 Convention on fishing and conservation of the living resources of the high seas – 1972 United Nations Conference on the human environment (Stockholm Conference) – 1992 Convention on biological diversity – 1995 Agreement for the implementation of the provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the conservation and management of straddling fish stocks and highly migratory fish stocks – 1992 United Nations Framework Convention on Climate Change – 2006 International Tropical Timber Agreement – 1985 ASEAN Convention – 1987 Zambezi Action Plan Agreement – 2000 Biosafety Protocol – 2010 Nagoya Protocol – 1992 OSPAR Convention – 1994 WTO General Agreement on Tariffs and Trade, (Article 20)
Inter-generational equity	<ul style="list-style-type: none"> – 1992 Rio Declaration on environment and development – 1992 United Nations Framework Convention on Climate Change – 1972 World Heritage Convention – 1978 Kuwait Convention, Preamble – 1983 Cartagena de Indias Protocol, Preamble – 1982 Jeddah Convention Art.1(1) – 1976 South Pacific Nature Convention, Preamble – 1977 ENMOD Convention, Preamble

that from the point of view of inter-generational responsibility the current generation is morally obliged to use scarce resources as efficiently as possible, and thus the use of geologically scarce mineral resources should be made sustainable.

In this paper we focus on the “strong sustainability” interpretation, because this interpretation is explicitly based on the principles of sustainable use of resources and inter-generational equity that are part of many international environmental agreements (Table 1).

Our interpretation of these principles is that the current generation is morally obliged to use geologically scarce resources in a sustainable way. This means that these resources must be kept available for future generations as well, to ensure that geologically scarce mineral resources do not become prohibitively expensive for future generations. A strict application of the strong sustainability concept would mean, however, that no generation (neither current, nor future) may extract any quantity of a mineral resource, because extraction always ultimately leads to exhaustion. This is neither practical nor necessary, because by sufficiently sparing on the geologically scarcest resources, humankind can buy time to work on problem solving in the future. Using this point of departure, Henckens et al. (2014) made the concept of sustainable extraction of mineral resources operational by formulating the following definition. “The extraction rate of a mineral resource is sustainable if it can provide 9 billion people with that mineral for at least 1000 years, assuming that the per capita use is equally divided over the countries of the world”. This definition reconciles both views (on weak sustainability and strong sustainability), because it recognizes that ultimately, exhaustion is unavoidable, but exhaustion of the geologically scarcest mineral resources in question is delayed for an acceptably long period of time. Using this definition, the reduction of extraction required has been calculated for four minerals: antimony (96% reduction required: Henckens et al. (2016b)), boron (44% reduction required: Henckens et al. 2015),

zinc (82% reduction required: Henckens et al. 2016a), and molybdenum (81% reduction required: Henckens et al.).

An interesting question is whether the sustainable use of geologically scarce mineral resources can be achieved automatically by the influence of the price mechanism of the free market system. Would the reaction of the price mechanism to increasing geological scarcity of mineral resources trigger a timely and sufficient reduction in the use of mineral resources? Although this question was asked by Dasgupta and Heal (1979, p. 2), it has not yet been unambiguously answered and remains relevant today.

According to Tilton (2001), (chapter 3) the price of a mineral is only a limited indicator for geological scarcity. This is supported by Seyhan et al. (2012) in their theoretical investigation of the exhaustion of the essential resource phosphorus. They concluded that the market price cannot serve as a reliable indicator of scarcity, because when on an optimal path, the price can fall temporarily, despite ongoing exhaustion. Farley and Costanza (2002) found that markets are not efficient mechanisms for allocating scarce resources. In a vision on a sustainable and desirable USA in 2100, they indicate that “most forms of natural capital will be recognized as inter-generational assets” (Farley and Costanza, 2002, p. 251). Famous in this context is the wager between the economist Julian Simon and the environmentalist Paul Ehrlich made in 1980, on the price development of commodities (Worstell, 2013). Ehrlich expected prices to increase, because of growing demand. Simon argued that more people mean more brains and better methods of extraction, combined with a more efficient use of primary materials. Although Simon won the bet for the 10-year period in question (1980–1990), it is not certain that the outcome can be extrapolated to any period in the (far) future.

The key question of this paper is whether the price mechanism of the free market system will timely and automatically lead to sufficient conservation of geologically scarce mineral resources for future generations. To answer this question, we will first discuss the concept of geological scarcity. How scarce is scarce? We will distinguish very scarce, scarce, and moderately scarce mineral resources.

In Section 3 we explore how prices of minerals might react to increasing geological scarcity in general. Then we study actual trends in market prices of mineral resources for the period between 1900 and 2013 (Section 4). Finally, we analyze whether the price development in that period shows that price is related to geological scarcity (Section 5). Our conclusions are presented in Section 6.

2. Geological scarcity of mineral resources

Geological scarcity of mineral resources must be distinguished from economic scarcity. Economic scarcity of mineral resources is the umbrella concept and can be caused not only by geological scarcity, but also by many other factors. Ultimately, the market price is determined by the balance between demand and supply. A higher demand for a commodity may be caused by new applications (e.g. rare earth elements in electronics), or the fast industrial development of large countries such as China and India. A lower demand may be caused by the discovery of cheaper and/or better substitutes for an application. A higher or lower supply can be artificially caused by a political decision of monopoly or oligopoly countries (e.g. oil-producing countries). Factors causing a reduction in supply include accidents, strikes, and geopolitical actions (e.g. boycotts). The main difference between the latter causes of scarcity and geological scarcity is that geological scarcity is a more structural phenomenon, whereas the other causes have a more cyclical character.

Globally, extraction of minerals is increasing rapidly.

Simultaneously, the ore grades mined are declining. Many mines in the old industrial regions of the world (USA and Europe) have been closed due to low ore grades. Prior et al. (2012) show that ore grades in Australia, an important mineral-producing country, have declined by a factor of 2–5 since the beginning of mining in that country, and that environmental and social costs are increasing at the same pace. They argue that mineral production in Australia has become unsustainable because of the high external costs. In the USA, the grade of mined copper has declined from more than 2% in the early part of the 20th century to 0.5% at the beginning of the 21st century (Tilton, 2003). During the same period and also in the USA, the grade of iron ore declined from 60% to 20% (Tilton, 2003).

The growth of global production and consumption is determined by a combination of population growth and GDP per capita increase. The rising trend in raw materials use is partly offset by increasing material efficiency and recycling. The UN expects that population growth will level off by the end of the 21st century (United Nations, 2011). However, thereafter GDP per capita will probably continue to grow. There is a positive relationship between GDP and metal consumption: the wealthier a country, the higher its metal use per capita (Graedel and Cao, 2010). But from a certain GDP onward, materials consumption per capita does not necessarily continue to increase concomitantly with GDP, as shown by Halada et al. (2008) and UNEP (2011b). These studies indicate that consumption of materials may decouple from GDP growth. According to Halada et al. (2008) this decoupling will start from a per capita GDP of about USD 10,000 per capita (1980 dollars). UNEP (2011b) has developed a scenario showing that from 2050 stabilization of the use of raw materials would be possible, assuming consumption worldwide continues to grow by 3% per annum until 2050. A 3% growth scenario is prudent, given the historical growth rates of the extraction of several important mineral resources (Table 2).

This scenario assumes net zero growth of raw materials use in the industrialized world and a higher (> 3%) growth of raw materials consumption in the developing part of the world. The “freeze” scenario for the industrialized part of the world is supported by Bringezu and Schütz (2001), Eurostat (2002), Weisz et al. (2006), NIES/MOE (2007), and Roglich et al. (2008). The “catching up” scenario for the rest of the world is supported by studies of Giljum (2002), Gonzalez-Martinez and Schandl (2008), Chen and Qiao (2001), Perez-Rincon (2006), Russi et al. (2008), and OECD (2008). In the “freeze and catching up” scenario, the developing part of the world will have caught up with the industrialized part of the world in 2050, and from that year on it would be possible to globally decouple primary materials consumption from further GDP growth. The global primary materials consumption level per capita that will be attained in 2050 would then equal the level prevailing today in the industrial world. In this scenario it is assumed that from 2050 onwards total annual consumption of primary materials will stabilize at a level of about 3.3 times the level in 2010. This is a large amount, despite the optimistic assumption that the annual use of mineral resources would stop increasing after 2050. This therefore raises the question of whether at this high level of primary materials

consumption (which equals extraction), exhaustion of the geologically scarcest materials might become a problem.

Not all mineral resources are equally scarce from a geological point of view. The extractability of a mineral from the earth's crust depends on its concentration in ores. Phillips (1977), Van Vuuren et al. (1999), Skinner (2001), and Tilton (2003) suppose that the distribution of grade and tonnage of major elements in the earth's crust (> 0.1 wt% average content) has a unimodal bell shape. They suppose that the distribution of so-called *minor* elements (< 0.1 wt% average content) is bimodal. See Fig. 1.

Mining companies do not plan extraction further than about 30 years ahead, so therefore, the combined data from mining companies on reserves do not reflect the extractable global resources. The extractable global resources are represented by the right-hand tails of the two graphs in Fig. 1. The so-called “mineralogical barrier” is the threshold grade between extractability and non-extractability. However, this threshold grade is not immutable. The grade from which a mineral is considered extractable depends on the willingness-to-pay of the market. With technological development, extractability will extend to lower grades. The amount of mineral in common rocks, the left-hand parts of the graphs in Fig. 1, is huge compared to the amount that is considered extractable. Although, technically speaking, low grades are extractable as well, this may not happen due to the high energy costs of extracting a mineral from common rock. Skinner (1976) estimates that the extractable amount of copper (represented by the area under the curve to the right of the mineralogical barrier of the bimodal curve of Fig. 1) is between 0.01% and 0.001% of the total amount of copper in the earth's crust. On the basis of the distribution of known deposits of minerals, Rankin (2011) points out that the total amount of enriched deposits is proportional to the crustal occurrence of the mineral. This means that the extractable amount of all mineral resources would be between 0.01% and 0.001%. Erickson (1973) and the UNEP International Resource Panel (2011a) come to the same conclusion. According to the UNEP International Resource Panel (2011a), a reasonable estimate of the upper limit of the extractable global resources is 0.01% of the total amount of a mineral in the top 1 km of the earth's continental crust. The UNEP International Resource Panel has compared the reserve base estimates of the United States Geological Survey with the 0.01% estimate for the extractable global resources. Their conclusion is that the 0.01% estimate results in an average amount of extractable global resources that is approximately 35 times higher than the estimates given by USGS in its latest reserve base data (2009). The 0.01% estimate is rough and general, but we have been unable to find any other more precise estimate of the amount of extractable global resources in the literature.

Departing from the 0.01% estimate for the total amount of extractable global resources, Henckens et al. (2014) subdivided 60 metals and metalloids into four scarcity classes (Table 1). To calculate the exhaustion periods shown in Table 3, they divided the extractable global resources of each element by the extracted quantity of that element as calculated for 2050.

The assumptions underlying the figures in Table 3 are that after 2050 the extraction rate remains stable, the current recycling rates

Table 2
Incremental extraction of seven mineral resources worldwide: average annual increase over 1900–2013, 1950–2013, and 2000–2013. All figures calculated by the authors based on United States Geological Survey Historical Statistics, 2015.

Average annual increase in extraction rate								
Period considered	Molybdenum	Chromium	Nickel	Copper	Zinc	Lead	Tin	Grand average
1900–2013	16.5%	7.6%	7.3%	3.9%	3.5%	2.8%	1.9%	6.2%
1950–2013	6.0%	4.9%	4.5%	3.5%	3.4%	2.3%	1.2%	3.7%
2000–2013	5.4%	5.3%	3.3%	2.6%	3.9%	4.4%	1.8%	3.8%

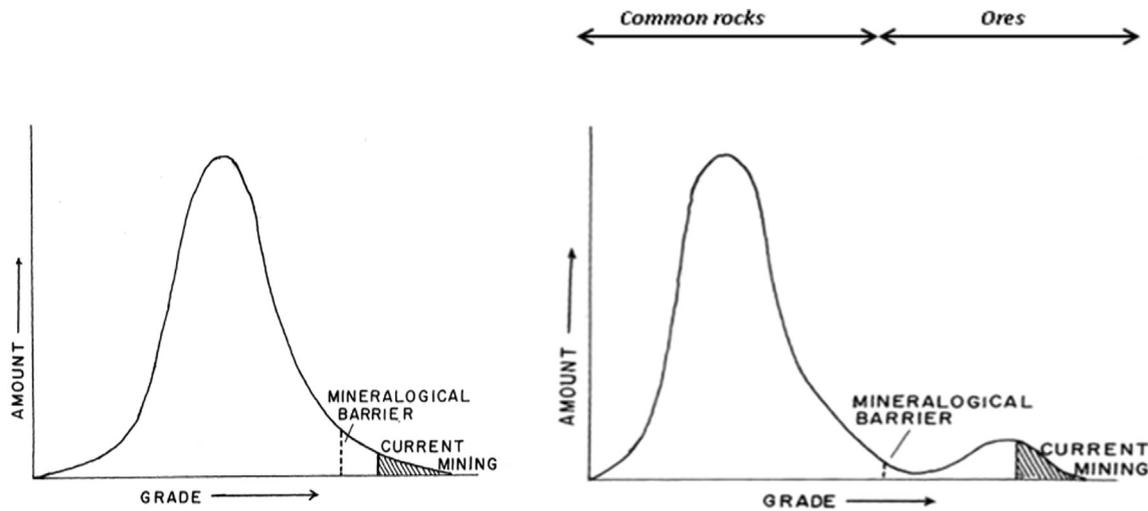


Fig. 1. Grade and tonnage distribution of major elements (> 0.1 wt%, such as aluminum, iron, titanium) in the earth's crust (left-hand graph) and minor elements (< 0.1 wt%, such as copper zinc, nickel, tin, gold, lead) (right-hand graph). Assumption based on Skinner (2001).

are maintained, and there is no substitution and neither are measures introduced to improve efficiency of raw materials consumption. In practice, recycling will improve, certain applications will be substituted, and efficiency of raw materials use will increase. However, new applications may be developed, increasing the demand for the mineral. Also, the growth of mineral consumption may not level off in 2050, or it may be higher than 3% per year. Table 3 is intended to clarify the distinction between very scarce, scarce, moderately scarce, and non-scarce, and to provide an order of magnitude of exhaustion periods, if cumulative extraction were to be extrapolated into the future assuming that no further change will take place (such as extra substitution and improved recycling).

An exhaustion period of 1000 years for making the distinction between scarce and not scarce is a rather arbitrary choice. We have followed the working definition proposed by Henckens et al. (2014) for sustainable extraction that was mentioned in the introductory section. The argument of Henckens et al. (2014) is that

while any allowable exhaustion period would be arbitrary as point of departure for a working definition for sustainable extraction, a period of 100 years is perceived to be too short, as it would allow exhaustion to occur at relatively short notice, whereas a period of 10,000 years would be unnecessarily long. A period of 1000 years would entail delaying exhaustion for a considerable period of time, long enough to be able to organize a circular economy and to minimize extraction of new mineral resources to the amount that is dispersed in the environment by unavoidable dissipation.

The conclusion of Henckens et al. (2014) is that the 17 elements in the three left-hand columns of Table 1 need special attention. From a relatively near point in the future onward, these seventeen geologically scarce minerals will no longer be available for future generations to the extent and at the price that they are available for the current generation, unless their extraction is substantially reduced.

Exhaustion of a resource does not mean there will be complete absence of the commodity from that moment on. The earth's crust

Table 3

Exhaustion periods of 60 elements (years after 2050) under the assumption that the extraction of all elements mentioned increases annually by 3% until 2050, after which it levels off. Metals and metalloids classified according to geological scarcity. EGR=extractable global resources as defined by UNEP (2011a) (Source: Henckens et al. (2014)). Rounded figures.

Very scarce (EGR exhausted before 2050)	Scarce (EGR exhaustion time < 100 years after 2050)	Moderately scarce (EGR exhaustion time between 100 and 1000 years after 2050)	Not scarce (EGR exhaustion time > 1000 years after 2050)
Antimony	-10	Gold	10
		Molybdenum	50
		Rhenium	80
		Zinc	50
		Arsenic	400
		Bismuth	200
		Boron	200
		Cadmium	500
		Chromium	200
		Copper	100
		Iron	300
		Lead	300
		Nickel	300
		Silver	200
		Tin	200
		Tungsten	300
		Aluminum	20,000
		Barium	1000
		Beryllium	200,000
		Cobalt	2000
		Gallium	1,000,000
		Germanium	200,000
		Indium	10,000
		Lithium	9000
		Magnesium	30,000
		Manganese	2000
		Mercury	400,000
		Niobium	2000
		Platinum Group Metals	1000
		Rare Earth Metals	20,000
		Selenium	300,000
		Strontium	10,000
		Tantalum	20,000
		Thallium	1,000,000
		Titanium	10,000
		Uranium	2000
		Vanadium	20,000
		Zirconium	2000

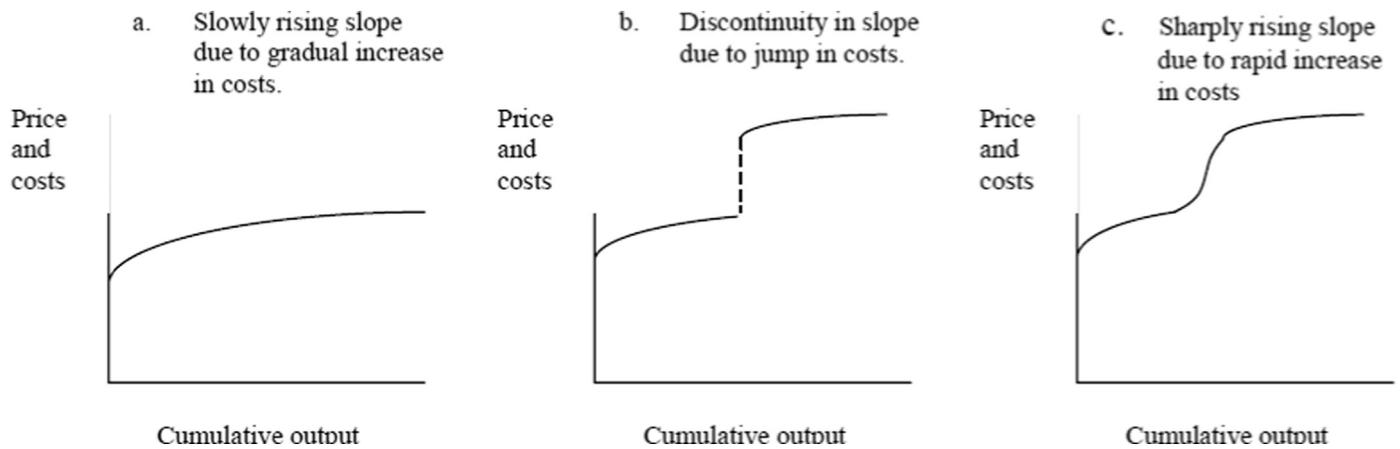


Fig. 2. Illustrative cumulative supply curves (after Tilton and Skinner (1987)).

will still contain much, even most, of the resource. But these low-grade occurrences can only be extracted at (much) higher costs. The rising cost may be (partly) offset by new technologies and lower energy costs, if the latter were a realistic assumption. Moreover, unlike fossil fuels, elements such as copper or zinc will not disappear through being used. They will be dissipated in the environment or be contained in end-of-life products, from which, technically, they can be rescued and recycled. Therefore, one might wonder whether geological scarcity will really become a problem for future generations. After all, minerals that are extracted by the current generation will be part of the infrastructure and commodities remaining for future generations. Moreover, past and current generations have invented recycling technologies, and such technological development will continue. Future generations might not need to extract any more primary raw materials, instead using and applying what they have inherited from previous generations. However, mining results in a mineral being isolated and concentrated, after which it is applied in many different products. In these applications, or by use, the mineral is diluted again. Inevitably, some of it will be dissipated by disposal in landfills, waste incineration, or directly by usage, such as by use in fertilizers, washing products, or paint. The main application of zinc is to protect steel against corrosion. A substantial part of this zinc dissolves in rainwater and is washed away in surface water, groundwater, and seawater. Some of the boron used is in fertilizer and ends up directly or indirectly in groundwater or in sewer systems. The main application of molybdenum is in stainless steel. From end-of-life products, an important part of molybdenum is down-cycled into lower quality steel products, where it no longer has a function.

3. Trends in market price for mineral resources

In this paper we investigate the long-term price trends of mineral resources in order to examine how these are affected by geological scarcity. This will result in a general long-term price development hypothesis for mineral resources. On the basis of this hypothesis we will be able to compare the actual market price development of mineral resources with the price development that can be expected on the basis of the hypothesis.

It should be noticed that historical prices for mineral commodities do not reflect the costs of extraction and processing only. World production of some minerals is largely concentrated in only one or a few countries, so these producers can dictate the price for a shorter or longer time. Other factors that may influence the market price are geopolitical circumstances, such as boycotts of an

important producer, wars, accidents, or strikes. Also, a strong increase of demand can cause the supply of commodities to the market to lag behind the demand, so that prices will increase. Another important circumstance in which the market price does not reflect the production costs is when a relatively large proportion of the resource is obtained as a by-product of the production of other mineral resources, as is the case, for instance, for rhenium, molybdenum, and cobalt. The largest part of the volume of these minerals extracted worldwide is a by-product of copper extraction (rhenium: 90%, cobalt: 70%, molybdenum: 60%) (Copper Alliance, 2015). The market prices of by-product minerals will mainly be determined by the trade-off between the volume of by-product generated and the market demand for this by-product.

Although growing geological scarcity is mitigated by the current state of technology, the increasing dependence of humankind on ever lower ore grades and remoter and deeper mines is irreversible. This means that in the longer term, the bottom price for a mineral is determined by the marginal extraction costs of that mineral. Cyclical variations of the market price are superposed on the extraction costs. Nevertheless, the market price will not decrease structurally below the level of the marginal costs for extraction and exploration, because mine owners will not want to work at a loss. At that point, mines will be closed, as has happened to many mines in Europe and the United States.

3.1. The relationship between extraction costs and geological scarcity

The cumulative supply curve (or cumulative availability curve) is a theoretical concept that reflects how the total of cumulative supply of a mineral could vary over *all time* with the extraction costs (Tilton and Skinner, 1987). For mineral commodities, cumulative supply at a certain price is fixed by the amount of the mineral that can be produced profitably at that price. A rising price permits the extraction of a lower grade mineral and higher external costs, if these are included in the price. The higher the price that consumers are willing to pay for a mineral, the greater its possible cumulative extraction.

The type of distribution of the resource in the earth's crust (unimodally or bimodally) determines the slope of the cumulative curve. Tilton and Skinner (1987) present three model cumulative supply curves (See Fig. 2).

In Fig. 2a a small price increase allows a large increase in cumulative supply and, inversely, a growing demand will only trigger a relatively small increase in price. This type of curve belongs typically to a mineral with the bell-shape unimodal distribution of abundant minerals in the earth's crust, such as aluminum. If a mineral is bimodally distributed in the earth's crust, the

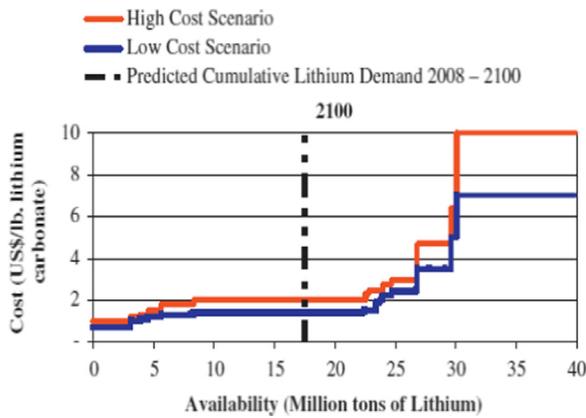


Fig. 3. Cumulative availability curve for lithium. Derived from Yaksic and Tilton (2009). On the vertical axis the costs are expressed in USD per lb. of lithium. 1 lb. is 0.45359237 kg.

cumulative supply curve will have the form shown in Fig. 2b or c. The steep part of the curves in Fig. 2b and c represents the so-called mineralogical barrier between the occurrence of a mineral in enriched ores and its occurrence in common rock. Costs may rise by a factor of 10 to 1000 in a relatively short period of time (Steen and Borg, 2002).

Yaksic and Tilton (2009) have determined the cumulative availability curve for lithium (see Fig. 3). According to them, the 2009 price of lithium carbonate is USD 6 per kg. The right-hand – flat – part of the curve represents the situation when lithium is extracted from seawater (an almost inexhaustible source of lithium). The costs would then increase until USD 16–22 per kg (USD 7–10 per pound). Such costs do not seem to be insurmountable for application of lithium in lithium batteries. It should be noted that only lithium, sodium, potassium, calcium, and chlorine are elements that can be extracted economically from seawater because of their relatively high abundance in seawater, as demonstrated by Bardi (2009).

In the future, technological development may also include mining of ocean floor deposits of minerals. According to Rankin (2011), the oceanic crust is too young for geological processes to have formed ores (Skinner 1976). But large areas of ocean floor contain deposits of minerals formed from erosion processes on the continents (Rankin, 2011). These may be explored and exploited in the future, although their proper extraction will be an environmental and technological challenge. Because large areas of the ocean floor have not yet been explored it is difficult to estimate the total amount of enriched deposits of mineral resources. The oceans cover about 70% of the earth's crust. It can therefore be prudently concluded that the extractable quantity of mineral deposits on the ocean floors may be substantial in an absolute sense, but will probably not be more important than the amounts available in the continental earth's crust. This means that the geological availability of various minerals on the sea bed will not be so high that the discussion on future geological scarcity of mineral resources will become irrelevant.

The maximum extraction cost of a mineral resource is determined by the cost of extraction from common rock or from seawater. Once this is the case, scarcity no longer plays a role. The quantities available in common rock and seawater are almost inexhaustible. Technically it is possible to extract minerals from common rock, but it is very expensive. According to Skinner (1976), the energy consumption for extracting copper from common rock is ten times higher than that for extracting copper from copper ore. This is supported by Harmsen et al. (2013), Bardi (2013), and Norgate and Jahanshahi (2010). Steen and Borg (2002) have calculated the costs of extraction of minerals from common

Table 4

Cost increase for the production of ore-like metal concentrates from common rock in a sustainable way, including the external costs, compared to current price level (Steen and Borg, 2002).

	Cost increase compared to current price level	Cost increase compared to current price level
Cd	4,000–100,000	Ni 40
Co	30	Pb 700
Cr	20	Sn 200
Cu	90	W 20,000–200,000
Mn	10	Zn 50

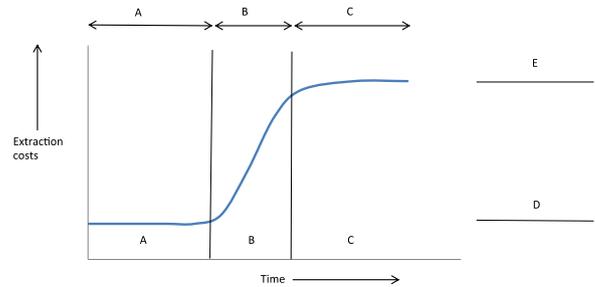


Fig. 4. Expected trend in extraction cost of mineral commodities. A: Period of relatively low extraction costs. We suppose that this period corresponds with the exhaustion periods indicated in Table 1. B: Period of increasing extraction costs. This is the transition period between the extraction of minerals from ores and extraction of minerals from common rock and seawater. C: Period of stable high extraction costs. Ores are exhausted. Minerals are extracted from common rock and seawater. D: Current extraction costs of commodities. E: Ultimate cost level for extraction of commodity from common rock or from seawater.

rock for a number of metals (see Table 4).

The above implies that ultimately the extraction costs of a mineral will asymptotically reach the costs of extraction of the mineral from common rock and/or seawater. This means that the graph describing the development of resource extraction costs over time, assuming that mineral extraction continues after ore exhaustion, is duck-shaped. See Fig. 4.

The duck shape is applicable for both major and minor elements. In the case of major elements, the slope of the curve (during time period B) will be gentle and stretched out, whereas in the case of minor elements with a bimodal distribution in the earth's crust the slope of the curve will be much steeper.

In practice the high price level connected to the high level extraction costs at the right-hand side of Fig. 4 will probably not be attained for most minerals in most applications. Depending on the application, from a certain price level on, a substitute will replace the mineral and the so-called choke price will be attained. The choke price is the price level at which the demand for a commodity for a given application will fall to zero because a substitute is available. Extraction will stop as soon as the choke price of a mineral for its last application is reached. Prediction of the specific form of Fig. 4 for a given element would be possible in principle but will be complex, e.g. because data are lacking on the distribution of minerals in the earth's crust or because of a lack of data on the availability of future substitutes which will delay exhaustion of ores.

An important question is how much time will elapse between leaving the low price level and reaching the high price level (the duration of the B period in Fig. 4). Will the market timely anticipate future scarcity and will prices start to rise appreciably a long time before scarcity of ore reserves is in sight, well before the A period in Fig. 4 has ended? This seems unlikely. The price will probably follow the extraction costs, which means that prices will start to increase only in period B. That would be too late, if humankind aims to conserve sufficient ores for future generations.

If scarcity increases rapidly and adequate substitutes are absent or few in number, the market price will probably rise relatively rapidly to a level sufficient to cover the higher costs of extraction or of developing suitable substitutes. However, even a quick price increase of a raw material may not have an immediate effect on demand. This depends on the share of the costs of the raw material in the total costs of its main product applications. A threefold price increase of a raw material may make an average end product no more than about 10% more expensive. This is based on the assumption that raw material prices nowadays usually make up only a small percentage of the cost of an end product (De Bruyn et al., 2009). Only if prices of raw materials were to increase by a factor 10–100 would this result in products that are in the order of 50% to five times more expensive. This means that the eventual price increase of a raw material due to exhaustion of the ores in which it is contained does not necessarily lead to a proportional decrease in the demand for the raw material. The conclusion is that extraction of ores may continue at the same pace even when that they are practically exhausted. This will certainly be the case if a proper substitute is available. In that case mine owners may try

to make their capital as profitable as possible and try to sell as much as possible of the remaining ore before it becomes “worthless”. More information on the possible impact of substitutability, material efficiency improvement, and recycling on the long-term development of mineral resource prices is included in the [Supplementary data](#).

We expect that ultimately the price of mineral resources is determined by geological scarcity and is duck-shaped, as indicated in Fig. 4. The scarcer a mineral resource, the earlier the market price will start to increase.

4. Actual trends in mineral resource market prices

To investigate whether geological scarcity is visible in the price development of a mineral resource we selected 38 minerals, including two groups of minerals: REE (Rare Earth Elements) and PGM (Platinum Group Metals). They have various geological degrees of scarcity. Table 5 shows the differences between the exhaustion rates of the four scarcity groups. In this context,

Table 5
Ten-year exhaustion rate in relation to geological scarcity.

		Total world extraction between 2004 and 2013 (USGS, 2015)	Extractable Global Resources (derived from approach of UNEP (2011a))	Total extraction in decade between 2004 and 2013 as proportion of the extractable global resources	
Very scarce minerals	Antimony	1,722,000	8,000,000	22%	
Scarce minerals	Molybdenum	2,211,000	60,000,000	4%	
	Gold				
	Rhenium				
Moderately scarce minerals	Zinc	116,000,000	2,800,000,000	4%	
	Tin	2,724,000	220,000,000	1%	
	Chromium	69,500,000	3,300,000,000	2%	
	Copper*	160,000,000	7,500,000,000	2%	
	Lead*	40,860,000	3,750,000,000	1%	
	Silver	224,000	20,000,000	1%	
	Arsenic	465,300	60,000,000	1%	
	Bismuth	69,500	5,200,000	1%	
	Cadmium	208,400	39,000,000	1%	
	Iron ore (gross weight)	22,830,000,000	5,700,000,000,000	0.4%	
	Nickel	16,510,000	1,800,000,000	1%	
	Tungsten	659,200	80,000,000	1%	
	Tin	2,724,000	220,000,000	1%	
	Chromium	69,500,000	3,300,000,000	2%	
	Boron (as B ₂ O ₃)	41,330,000	1,900,000,000	2%	
	Non-scarce minerals	Aluminum	389,500,000	3,200,000,000,000	0.01%
		Magnesium	52,050,000	530,000,000,000	0.01%
Beryllium		1910	120,000,000	0.002%	
Barium		42,802,525	22,000,000,000	0.2%	
Cobalt		655,600	680,000,000	0.1%	
Gallium		1692	680,000,000	0.0002%	
Germanium		1168	64,000,000	0.002%	
Mercury		16,930	2,700,000,000	0.001%	
Indium		6585	20,000,000	0.03%	
Lithium		4,587,000	800,000,000	0.6%	
Manganese		132,000,000	24,000,000,000	0.6%	
Niobium		579,400	480,000,000	0.1%	
Rare Earth Elements (as RE oxide equivalent)		1,211,000	6,700,000,000	0.02%	
Platinum Group Metals		4755	1,900,000	0.3%	
Selenium		20,810	2,000,000,000	0.001%	
Tantalum		9908	4,300,000,000	0.0002%	
Strontium		4,126,000	14,000,000,000	0.03%	
Titanium		100,370	170,000,000,000	0.0001%	
Vanadium		642,400	4,300,000,000	0.01%	

* The extractable global resources of copper and lead calculated on the basis of 0.01% of their amounts in the top 1 km of the earth's crust appear to be lower than the USGS Reserve Base figures. Therefore, for these two elements, the supposed extractable global resources have been increased to 2.5 times the USGS Reserve Base figures. This is in line with Rankin (2011, p. 303), who compared the results of an assessment of undiscovered deposits of gold, silver, copper, lead, and zinc in the USA with the ratio of the (UNEP) extractable global resources to the (USGS) reserve base.

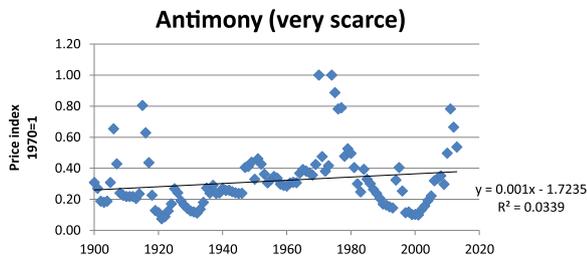


Fig. 5. Actual price trend for antimony.

exhaustion rate is defined as the total amount of the mineral extracted in the 10-year period 2004–2013 as a proportion of the extractable global resources (as derived from UNEP, 2011a).

We have carried out a trend analysis of the market price development of each of the mineral resources of Table 5. Fig. 5 presents the trend analysis for antimony. The individual results for the other minerals are included in the Supplementary data.

The rate of increase or decrease of the real price of minerals over time is represented by the coefficients of the linear functions. If the coefficient is positive, the long-term trend is a price increase. If the coefficient is negative, the long-term trend is a price decrease. The higher (or lower) the coefficient, the faster the price increase (or decrease).

The line that represents the trend in the price of a specific mineral over time is calculated by the least squares linear

regression method. The quality of the fit is presented by R^2 . The so-called P -value of the coefficient represents the probability that the value of the coefficient is determined by chance. If the P -value is smaller than or equal to 0.05, the slope of the linear function (the coefficient) is considered to represent the price trend of the mineral in question over time in a significant way. Table 6 presents the coefficients and the related P -values for all the minerals that we have investigated. We compared these coefficients with the geological scarcity of the mineral. To obtain a simple number for the degree of scarcity, we expressed the geological scarcity as the natural logarithm of 1,000,000 divided by the exhaustion time after 2020. This results in a scale from 0 to 11:

- 11: very scarce
- between 9 and 10: scarce
- between 7 and 9: moderately scarce
- < 7: not scarce.

The significance indicates whether there is a significant correlation between the coefficient of the calculated linear function describing the price development, and the observed price trend.

Table 6 is graphically presented in Fig. 6. In this figure we have only taken into consideration the 25 mineral resources with significant results (coefficients with a P -value ≤ 0.05). A regression analysis of the data shows that there is no significant correlation between geological scarcity and price trend. The P -value is 0.98. See the supplementary data. A second observation is that the price trend coefficients are all near to zero, regardless of geological scarcity.

Table 6
Price-trend-over-time coefficient and geological scarcity.

Mineral	Period considered	Price-trend-over-time coefficient	P -value of price-trend-over-time coefficient	Significance	Scarcity ^a	Scarcity class
Antimony	1900–2013	0.0010	0.050	*	10.8	Very scarce
Gold	1900–2013	0.0202	5.3E-08	***	10.2	Scarce
Zinc	1900–2013	–0.0036	0.0025	**	9.5	
Molybdenum	1912–2013	0.0022	0.45	Ns	9.4	
Rhenium	1980–2013	0.0062	0.11	Ns	9.1	
Copper	1920–2013	0.0020	0.010	**	8.8	Moderately scarce
Chromium	1900–2013	0.015	1.9E-13	***	8.6	
Boron	1900–2013	–0.0066	0.0047	**	8.4	
Tin	1900–2013	0.0024	0.027	*	8.3	
Silver	1900–2013	0.0037	0.068	Ns	8.2	
Lead	1900–2013	–0.0030	0.00038	**	8.2	
Bismuth	1900–2013	–0.010	1.1E-22	***	8.6	
Nickel	1920–2013	0.0047	0.00002	***	8.0	
Iron	1900–2013	0.0043	9.7E-07	***	7.9	
Tungsten	1900–2013	–0.000092	0.95	Ns	7.9	
Arsenic	1925–2013	–0.0059	0.0007	***	7.7	
Cadmium	1900–2013	–0.0070	7.2E-17	***	7.5	
Barium	1900–2013	–0.0054	2.6E-06	***	6.6	Not scarce
PGM	1940–2013	0.0071	3.2E-05	***	6.6	
Manganese	1900–2013	0.012	5.3E-08	***	6.5	
Cobalt	1900–2013	–0.013	5.3E-05	***	6.1	
Niobium	1964–2000	–0.015	0.10	Ns	6.1	
Lithium	1960–2013	–0.015	1.2E-11	***	4.7	
Indium	1946–2013	–0.0057	0.11	Ns	4.6	
Strontium	1935–2013	0.022	9.0E-05	***	4.5	
REE	1960–2013	0.11	0.0014	**	4.2	
Tantalum	1964–2013	–0.0033	0.82	Ns	4.0	
Vanadium	1910–2013	–0.011	6.4E-09	***	3.8	
Aluminum	1940–2013	–0.0097	2.1E-16	***	3.7	
Magnesium	1950–2013	–0.0021	0.0012	**	3.6	
Germanium	1960–2013	–0.0047	0.093	Ns	1.8	
Beryllium	1940–2013	–0.019	1.4E-12	***	1.7	
Selenium	1920–2013	–0.0012	0.383	Ns	1.2	
Mercury	1900–2013	–0.0028	0.0029	**	1.0	
Gallium	1980–2013	–0.0044	1.5E-07	***	–0.1	

^a Scarcity is expressed as $\ln(1,000,000/\text{exhaustion time after 2020})$.

Geological scarcity versus price trend

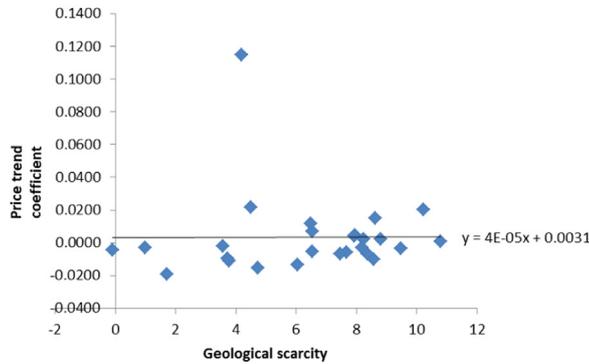


Fig. 6. Geological scarcity versus price trend. Geological scarcity is expressed as $\ln(1,000,000/\text{exhaustion time after 2020})$.

5. The relation between geological scarcity of minerals and their price trend

5.1. Although prices fluctuate in the course of time, it is striking that the real price of the investigated minerals remains remarkably stable over a long period

The hypothesis, as explained in Section 3, is that after an initial price decrease at the start-up of extraction of a mineral, the market price of that mineral resource will remain stable for a long time. Then, exhaustion of ores will lead to a relatively fast price increase. The greater the geological scarcity of the mineral, the earlier the price increase will start.

The price trend analysis of 38 minerals for the period 1900–2013 demonstrates that none of the minerals considered shows a fast price increase. For a long time, price changes (whether an increase or decrease) are very small. Regression analysis demonstrates that there has been no significant difference in price trends between geologically scarce minerals and geologically abundant minerals thus far. The data and the detailed results of the regression analysis are included in the Supplementary data.

Our conclusion is that, thus far, viewed over the long term, the prices of all minerals considered have stayed quite stable (shown by the very low slope values in Table 4 and Fig. 6), regardless of their scarcity. The observation of stable prices is in line with the conclusions of Krautkraemer (1998).

We used the inflation correction figures provided by the United States Geological Survey (2015). USGS uses the official Consumer Price Index provided by the Bureau of Labor Statistics. However, according to Svedberg and Tilton (2003), the deflator used by USGS overestimates the inflation. They contend that the real price of copper, nickel and silver would fall over the long term (130 years), whereas the real prices of lead and zinc would be more or less constant on the long run. Cuddington (2010) and Fernandez (2012) also support the conclusion that the real prices of mineral resources have not changed much over a long period of time.

We hypothesized that the prices of geologically scarcer minerals will start rising earlier than the prices of less scarce minerals, but thus far the market has not differentiated on the basis of future geological scarcity. Hence, geological scarcity is not yet so critical that the market reacts. The market price does not (yet) reflect the large differences in geological scarcity of the minerals considered. This phenomenon might be explained as follows. The time horizon at which the effects of geological scarcity will be felt is at least several decades to centuries away. The time horizon of market prices seems to be some years to about a decade maximum, taking into consideration that the maximum forward time for futures on the London Metal Exchange is 123 months.

Table 7

Unit values of commodities in the USA in 2010, expressed in 1998 USD per kilogram. Derived from USGS (2015).

	2010 unit value in the USA per kg, expressed in 1998 USD, rounded
Scarce minerals	
Antimony	7
Molybdenum	26
Zinc	2
Moderately scarce minerals	
Tin	20
Chromium	2
Copper	6
Lead	2
Boron (as B ₂ O ₃)	0.5
Non-scarce minerals	
Aluminum	2
Magnesium (as MgO)	0.4
Beryllium	375
Titanium (as TiO ₂)	2
Vanadium	19

Table 7 shows that the absolute prices of minerals is not related to geological scarcity either. The most expensive mineral (beryllium) is part of the group of non-scarce minerals, and one of the cheaper minerals is zinc, which belongs to the group of scarce minerals.

On the basis of the analysis of the historical price trends we conclude that geological scarcity is not yet a factor with a discernible influence on the pricing of mineral resources. It remains unclear how near to exhaustion the market will react with price increases linked to geological scarcity. It also remains unclear whether – at the moment the market starts to reflect geological scarcity – a sufficient amount of the mineral resource will remain for extraction by future generations.

6. Conclusions and discussion

The question addressed in this paper is whether the price mechanism of the free market system can be expected to slow down the extraction of geologically scarce minerals automatically and timely, in order to keep sufficient resources available for future generations. By comparing the real price development of commodities of varying geological scarcity over a long period of time, we investigated whether the price trends of mineral resources are related to geological scarcity. A limitation of the straightforward regression analysis of time series data applied in this study is that it is based on a large number of assumptions about the behavior of the variables, such as implied by stationarity of the system. We are aware that the relationships may become affected if non-stationary processes are involved.

We conclude that despite fluctuations in mineral resource prices, there is no significant correlation between the geological scarcity of a mineral resource and its price trend for the period that we have considered. The price trend of an abundant resource with sufficient geological reserves for thousands of years does not differ significantly from the price trend of a geologically scarce mineral resource whose ores may be exhausted within decades or a century. We therefore argue that we cannot be certain that the price mechanism of the free market system will lead to timely, automatic, and sufficient conservation of geologically scarce non-renewable mineral resources for future generations. When the point is reached that the ores of a geologically scarce mineral are nearly exhausted, the resource price is expected to increase rapidly. We raise the question of whether this is sufficiently timely for adequate conservation of geologically scarce mineral resources for future generations. We also question whether increased recycling of the stocks of minerals that have accumulated

in society will eventually be sufficient to solve scarcity for future generations. Inevitably, some of the minerals will dissipate into the environment. Because of these concerns we suggest international policy measures be created and implemented to increase the price of the scarcest mineral resources, thus promoting accelerated substitution and recycling and safeguarding a sufficient supply of the geologically scarcest mineral resources for future generations.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.resourpol.2016.04.012>.

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