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Scarce mineral resources: Extraction, consumption and limits of sustainability

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ABSTRACT

The interests of the current and future generations concerning the access to and the use of geologically scarce mineral resources diverge. This article explores whether this apparent irreconcilability can be resolved. It is investigated how far the extraction rate of thirteen scarce raw materials can be reduced while simultaneously increasing the services they provide worldwide to the level prevailing in developed countries in 2020. The scarce raw materials considered are antimony, bismuth, boron, chromium, copper, gold, indium, molybdenum, nickel, silver, tin, tungsten, and zinc. Indicative estimates of how long these mineral resources will be available for humanity are calculated, assuming (1)the world population stabilizes at ten billion people, (2) the global service level of these resources attains that prevailing in developed countries in 2020 and (3) maximum resource-saving measures are taken. The conclusion is that immediate implementation of the most stringent resource-saving measures could extend the estimated exhaustion periods of most of the scarcest raw materials by an average factor of approximately four, even while simultaneously increasing the global service level of these resources by a factor four as well. Without sufficient and adequate resource saving measures it will be difficult or impossible for a substantial part of the future world population to attain the service level of mineral resources prevailing in developed countries at this moment. Moreover, without such measures, the period of time that future citizens of rich countries can continue enjoying the current service level of some of the scarcest mineral resources in their countries, will be severely limited.

1. Introduction

For some time, scientists and politicians have expressed concern about the impending exhaustion of mineral resources. Especially influential in this respect are Meadows et al. (1972, 1992). Among those who support their point of view are Kesler (1994), Diederen (2009) and Bardi (2013). The opinion of these so-called resource pessimists is that the Earth is finite and hence so are the mineral resources. They contend that if demand continues to grow, it is only a matter of time before the supply of resources is no longer able to meet demand. Other authors are more optimistic, arguing that technological development has huge potential to solve problems of scarcity (Barnett and Morse, 1963; Maurice and Smithson, 1984; Diamandis et al., 2012). These resource optimists find confirmation in the fact that the real prices of mineral resources have hardly increased over time (Henckens et al., 2016) and that the reserves of mineral resources (as defined by the US Geological Survey) have remained stable or have even increased. Resource optimists do not deny that it will eventually become more costly to extract resources from the Earth's crust, but they put their trust in humankind's resourcefulness in tackling problems.

This article explores whether and to what extent the apparently diametrically opposed points of view of the resource optimists and of the resource pessimists can be reconciled. On the one hand, the article adopts the resource pessimists' point of view that the extractable stocks of raw materials in the Earth's crust are limited in practice. This limitation arises not because of the presence or absence of minerals in the ground, but because of the economic constraints to resource extraction. The economic limits of extraction are co-determined by the considerable external costs of extraction arising from the impact of ever deeper and remoter mining on climate change and on the mine's surrounding environment. On the other hand, the article adopts the resource optimists' point of view about the technological opportunities to increase the availability of raw materials and to simultaneously reduce extraction by increasing the recovery efficiency at the mining stage, by substituting, by increasing material efficiency and recycling, and by decreasing downcycling and in-use dissipation.

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The best-known definition of sustainability is the Brundtland definition of sustainable development: *"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). Hence, in line with this definition, the goal of a responsible global mineral resources policy could be to increase the service level of mineral resources worldwide to the level prevailing in developed countries in 2020, while simultaneously decreasing the extraction rate of mineral resources as much as possible in order to keep sufficient mineral resources available for future generations for as long as possible.

The objectives of this article are: (1) to analyze which combination of measures can be taken to reduce the extraction of the scarcest mineral resources as much as possible; (2) to determine the minimum required extraction rate for the scarcest mineral resources for achieving a worldwide service level of these resources that is the same as that prevailing in developed countries in 2020; (3) assuming the world population stabilizes at ten billion people, to explore how long the scarcest mineral resources will remain sufficiently available for humanity after the maximum resource-saving measures have been implemented and the target global service level has been achieved.

Section 3 presents the ethical basis for the frugal use of raw materials. The applicable normative principles are derived from decades of international declarations and agreements, such as the Declaration of the United Nations Conference on the Human Environment (Stockholm, 1972), the UN Charter for Nature (1982), the sustainability definition of the World Commission on Environment and Development (1987), the United Nations Framework Convention on Climate Change (1992), the UNESCO Earth Charter (2000) and the 2030 UN Agenda for Sustainable Development (2015). Section 3 results in the conclusion that the average global per capita consumption of thirteen scarce mineral resources is approximately four times less than the per capita consumption of these resources in developed countries. In the remainder of this article, it will be explored under which conditions the global service level of these resources can be increased to the same service level as in developed countries in 2020 while simultaneously decreasing the extraction of mineral resources as much as possible.

In Section 4, the relative scarcity of mineral resources is identified. First, four different approaches for estimating the amount of ultimately available resources in the Earth's crust are presented. Then the amounts of available resources are compared with their current annual extraction rates and the assumed future trends in annual extraction rates, in order to obtain a rough indication of the exhaustion periods of different resources, which determines their scarcity. In the remainder of the article, the focus is on the scarcest mineral resources.

In Section 5, the potential and limits of different types of resource-saving measures for each of the scarcest mineral resources are explored The following measures are investigated: increasing recovery efficiency, substitution, increasing material efficiency, decreasing in-use dissipation, decreasing downcycling, and increasing recycling.

Section 6 investigates the potential decrease in the annual extraction rate of the scarcest mineral resources if maximum resource-saving measures are applied while simultaneously the worldwide service level of these resources is increased to the level in developed countries in 2020. Thereafter, assuming this scenario, it is estimated how long the mineral resources in question could be sufficiently available for humanity.

Finally, in Section 8, conclusions are drawn. Given the lack of data and the aim of the investigation, various assumptions had to be made; these are based on the scientific literature and many tend to be optimistic, because my aim is to investigate the urgency of resource-saving measures even under optimistic assumptions. The assumptions are always presented transparently. If more precise data become available in the future, the findings of this study could be adapted accordingly, following the same approach. The sensitivity analysis presented in Section 7 reveals the sensitivity of the findings to the assumptions made.

2. Methods and data

This study is an ex-ante evaluation of the availability of mineral resources for future generations. An ex-ante evaluation is necessarily based on assumptions regarding future developments. The assumptions were based on real data regarding the current situation and developments until now. In this framework, the present paper is based on literature research regarding the availability of different mineral resources; stocks and flow studies; consumption patterns of different mineral resources and their development until now; literature data on recyclability and substitutability of materials. When no clear data are available in the literature, or when data differ, own estimates are made on the basis of comparable minerals or situations.

Starting point and key issue in the study was that it was assumed that, in the future, an average citizen of any country in the world has right of access to mineral resources at the same service level as the average citizen of a developed country in 2020. Under this precondition, the approach of the study was to investigate, which material saving measures are necessary, and to what extent, for keeping sufficient mineral resources available for ten billion people during a period of at least 200 years, but preferably 500 years or 1000 years.

The paper makes optimistic assumptions regarding the future availability of scarce mineral resources and regarding the potential effectiveness of resource saving measures in the future. This has been done on purpose because of two reasons.

The first reason was that an important intention of the study is to gain insight whether or not there may rise a problem in the relatively near future with regard to the availability of certain scarce mineral resources, even when making optimistic assumptions.

The second reason was that optimistic assumptions are justified because history demonstrates that technological development has played an important role for enabling that mineral resources have remained available for approximately the same real price for a long time. Technological development has also allowed for an increasing effectiveness of resource saving measures.

In a sensitivity analysis, the impact of less optimistic assumptions was analyzed as well. This regards both the time period, that scarce mineral resources will still be available for future generations and the amounts of these resources.

This publication was based to a great extent on previous research of the author. The key data of that research are summarized in the Supplementary Information.

3. Mineral resources ethics

The basic principles of mineral resources ethics are:

- within the same generation all people have equal rights of access to mineral resources (Intragenerational Equity Principle)
- both the current and future generations have equal rights of access to mineral resources (Intergenerational Equity Principle)

Compliance with these two principles leads automatically to compliance with two other important principles of international environmental law: the Principle of Sustainable Use of Resources and the Sustainable Development Principle. The question is how these principles can be operationalized.

Our starting point is that change toward more equity should be Pareto efficient, meaning that developing countries should be better off in the future, while no country may be worse off. This means that the future service level of mineral resources worldwide should at least achieve the level prevailing in developed countries in 2020. To achieve this situation, the developed countries will have to take measures to freeze the service level of scarce mineral resources in their countries at the 2020 level and will have to allow and assist developing countries to catch up and achieve that level. In the United Nations Environment

Programme (UNEP, 2011b), this approach is called the *freeze and catching up scenario*.

The current service level of a mineral resource in a country is defined to be equal to the current consumption level of that resource expressed in grams per capita per year. Fig. 1 shows three possible strategies for decreasing the extraction of resources while maintaining the level of the services the resource delivers:

(1) substitution for 20%, which will reduce extraction by 20%
(2) additionally, a 50% reduction of dissipation, which will reduce extraction by a further 10%
(3) additionally, 50% end-of-life recycling, which will reduce extraction by a further 30% .

The extraction of resources can also be further decreased by increasing the recovery efficiency at the mining and beneficiation stages, and by increasing the material efficiency, for instance by extending the lifetime of products containing the scarce resource.

The estimated per capita consumption in developed countries and worldwide of thirteen scarce mineral resources in 2020 is presented in Table 1. Note that consumption concerns primary plus secondary resources.

The purpose of a sound resources policy is to encourage the implementation of measures that result in a worldwide consumption level that provides at least the same services as those developed countries enjoyed in 2020, while simultaneously decreasing the use of primary resources as much as possible.

The next section identifies the geologically scarcest mineral resources.

Table 1
Estimated per capita annual consumption of resources in developed countries and worldwide in 2020. For details on data and data sources, see Supplementary Information (C) and (F).

Resource	Estimated per capita annual consumption (in g) of resources in developed countries in 2020	Estimated per capita annual consumption (in g) of resources worldwide in 2020
Antimony	90	20
Bismuth	9	2
Boron	600	200
Chromium	8000	2000
Copper	10,000	3000
Gold	2	0.5
Indium	0.4	0.1
Molybdenum	200	40
Nickel	2000	400
Silver	20	4
Tin	200	50
Tungsten	60	20
Zinc	8000	2000

4. Geological scarcity of mineral resources

A measuring stick for the scarcity of a mineral resource is the duration of the period that the resource will still be available for an affordable price. This period depends on three factors: (1) the availability of the resource in the Earth's crust, (2) the extraction rate and its change (increase or decrease) over time, and (3) the technological developments increasing the efficiency of resources extraction and beneficiation. These factors are discussed in the sections below. An affordable price is considered to be one that does not differ from the current price either in real terms or structurally by more than an order of magnitude

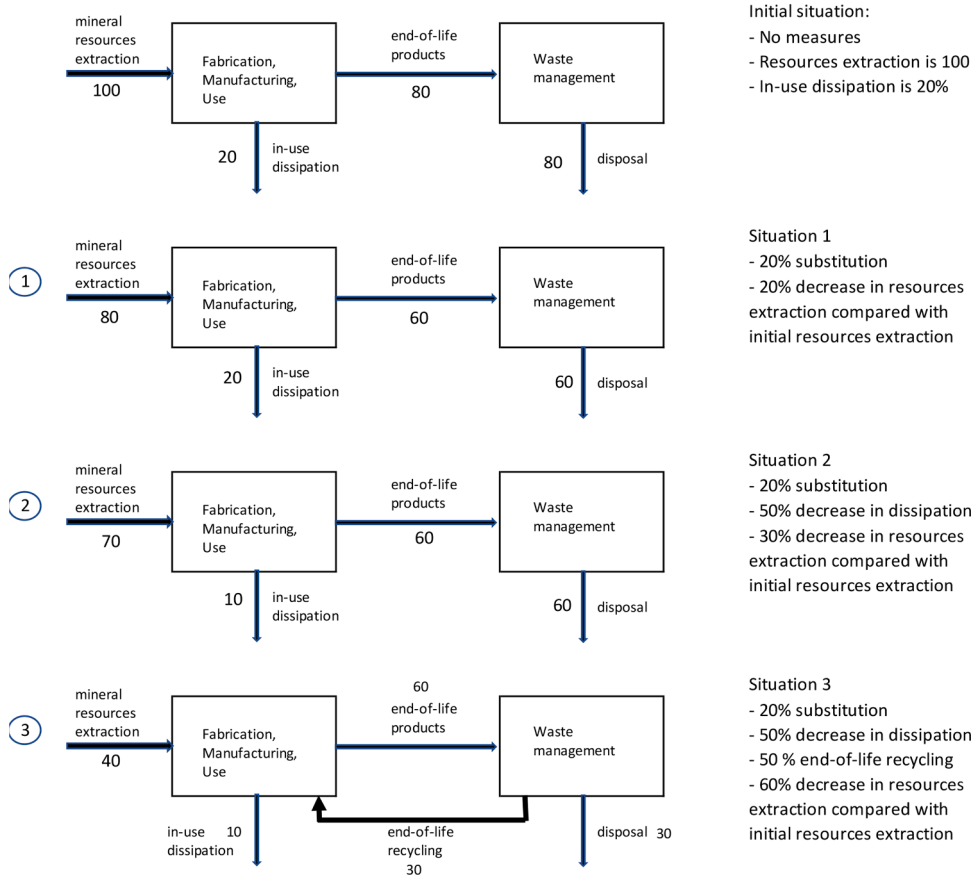


Fig. 1. Decreasing resources extraction while maintaining a constant level of service. The benchmark situation is the upper scheme. The quantities presented are annual amounts (expressed in units). In all cases, the service level remains 100 units per year.

(a factor of ten). In this regard, it is assumed that when the real extraction costs of a resource have become ten times higher than the current extraction costs, the resource is considered to be depleted in economic terms, because its extraction costs are no longer affordable: the precious low-hanging fruits have been taken and are not available for later generations. Note that this is not a physical depletion, because over 99% of the mineral is probably still in the Earth's crust but can only be extracted at a cost that is over ten times higher than today's.

4.1. The available amount of extractable mineral resources

Technically it will be possible to extract very low-grade minerals from the Earth's crust or from ocean water. Norgate and Jahanshahi (2010) provide information on different routes for extracting copper and nickel from grades of as low as 0.1%. However, it is no longer sensible to continue extracting a mineral when the point is reached at which the costs, including the external costs, exceed the returns, or when the mineral is only affordable to a few people. It is assumed that this point is reached when the real extraction costs have become ten times higher than the present-day costs. How much of a resource can still be extracted before this point is reached depends on how much the ore grades decrease, the size of the remaining deposits, their depth, their location (whether in remoter or more sensitive areas), and technological advances in mining and beneficiation.

From the scientific literature, four different approaches for estimating the extractable resources can be derived: three are generic and the fourth is specific per element. Approaches (1), (2), and (4) below are explained in detail in Supplementary Information(D).

(1) an approach assuming that the extractable amount of a resource is proportional to the average crustal abundance of that resource (Rankin, 2011; UNEP International Resource Panel on Sustainable Resource Management, 2011a; Skinner, 1976; Graedel and Nassar, 2015; Mookherjee and Panigrahi, 1994; Nishiyama and Adachi, 1995; Erickson 1973).
(2) an approach based on the global extrapolation of the relationship between the results of a thorough and relatively recent assessment of the amount of extractable resources of a number of minerals in the USA and the corresponding amount of these resources in the USA identified by the US Geological Survey(US Geological Survey, 2000).
(3) an approach based on so-called tectonic diffusion models developed by Kesler and Wilkinson (2008) for copper and gold. The tectonic diffusion model is based on the assumption that deposits of a certain type that were formed during a certain geological era move up and down randomly in the Earth's crust. Once they are exposed at the surface, crust erosion will dissipate them. This results in a skewed bell-shaped distribution of deposits over the depth of the crust. The model calculates the age frequency distribution of the deposits over the depth of the crust. The model is calibrated by comparing the results it produces with the presence of real deposits in the Earth's crust.
(4) an approach based on research on the available exploration data on specific resources.

Approach (3) has been elaborated for gold and copper (Kesler and Wilkinson, 2008; Wilkinson and Kesler, 2010), but has not yet been applied to other mineral resources. The result for gold falls between the results yielded by approaches (1) and (2); the result for copper is four times more than the highest result yielded by approaches (1) and (2) (Henckens, 2021). In all cases, approach (4) yields lower results than those of approaches 1 and 2.

We will use the generic approaches (1) and (2). Although these approaches yield results associated with large uncertainty, they can help in understanding whether a resource will become physically or economically exhausted within a matter of decades, centuries, or millennia. In this way, different resources can be compared with each other in terms of their exhaustibility. Table 2 provides an overview of the ultimately available amounts of thirty-six resources and groups of resources. The figures are probably optimistic, as they are the highest results of the two generic approaches (1) and (2), each of which are elaborated in Supplementary Information (D). The figures in Table 2 are based on the assumption that mining will be possible to a depth of 3 km in all cases, which is somewhat optimistic, as so far, with the exception of gold mines, mining has generally not extended below 1 km.

4.2. Growth of the extraction rate of mineral resources

The extraction of most resources has increased rapidly, especially since 1950. See Fig. 2.

The faster the extraction rate of a mineral resource increases, the sooner that resource will be depleted. To get an indicative idea of how fast the scarcest resources might run out, I consider two growth scenarios which are derived from Henckens (2016):

- Scenario 1: the increase in annual extraction of a mineral resource between 2015 and 2050 remains the same as the average increase in annual extraction between 1980 and 2015. The increase in annual extraction between 2050 and 2100 is 50% of the increase in annual extraction for the period 1980–2015. After 2100 there is no further increase in extraction.
- Scenario 2: the increase in annual extraction of a mineral resource until 2100 is equal to the average increase in annual extraction for the period 1980 −2015. The increase in annual extraction between 2100 and 2200 is 50% of the average increase in annual extraction for the period 1980–2015. After 2200 there is no further increase in extraction.

The average increase in annual extraction for thirty-six mineral commodities between 1985 and 2015 is presented in Table 3.

Both scenarios assume that the increase in extraction slows down in the future and finally stops. The justification for this assumption is the

Table 2
Estimate of the Ultimately Available Resources of thirty-six resources and resource groups. For details, see Supplementary Information (D).

Element	Estimate of the Ultimately Available Resources (rounded, Mt)	Element	Estimate of the Ultimately Available Resources (rounded, Mt)
Aluminum	10,000,000	Magnesium	3,000,000
Antimony	100	Manganese	100,000
Arsenic	200	Mercury	8
Barium	50,000	Molybdenum	200
Beryllium	300	Nickel	8000
Bismuth	20	Niobium	2000
Boron	3000	Platinum Group Metals[a]	3
Cadmium	40	Rare Earth Elements[b]	20,000
Chromium	35,000	Rhenium	0.1
Cobalt	3000	Selenium	6
Copper	10,000	Silver	20
Gallium	2000	Strontium	40,000
Germanium	200	Tantalum	200
Gold	2	Tin	300
Indium	30	Titanium	600,000
Iron	6,000,000	Tungsten	200
Lead	20,000	Vanadium	20,000
Lithium	2000	Zinc	30,000

[a] Platinum Group Metals are: ruthenium, rhodium, palladium, osmium, iridium, and platinum.
[b] Rare Earth Elements are scandium, yttrium, lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, and promethium.

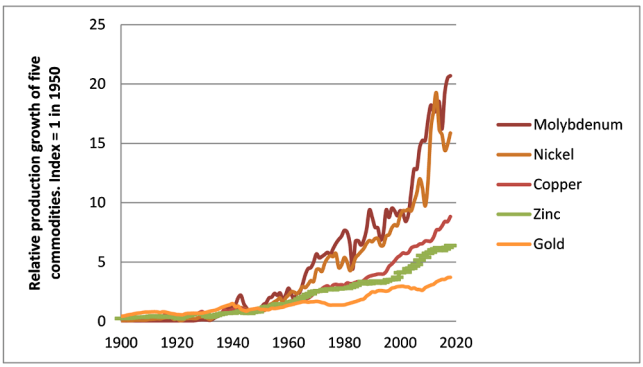


Fig. 2. Global extraction of five mineral commodities per annum from 1900 to 2020 (US Geological Survey, 2015, 2018c, 2019c). Derived from Henckens (2021).

Table 3
Increase in annual extraction of the thirty-six mineral commodities shown in Table 2, for the period 1980–2015 (US Geological Survey, 2017b).

Aluminum	3.8%	Germanium	0.9%	Platinum Group Metals	2.3%
Antimony	2.2%	Gold	2.7%	Rare Earth Elements	4.6%
Arsenic	0.5%	Indium	8.1%	Rhenium (linear)	1.1 kt/year
Barium	−0.1%	Iron	2.7%	Selenium	1.6%
Beryllium	−1.4%	Lead	1.0%	Silver	2.5%
Bismuth	3.8%	Lithium	5.4%	Strontium	3.8%
Boron	4.1%	Magnesium	2.6%	Tantalum	2.2%
Cadmium	0.7%	Manganese	1.7%	Tin (linear)	1.5 kt/year
Chromium	3.5%	Mercury	−2.1%	Titanium	1.8%
Cobalt	4.1%	Molybdenum	2.2%	Tungsten	1.6%
Copper	2.8%	Nickel	3.1%	Vanadium	2.2%
Gallium	9.8%	Niobium	4.2%	Zinc	2.2%

observation that in wealthier nations, consumption of many commodities starts to decouple from the GDP after the per capita GDP has reached a certain level (Halada et al., 2008; UNEP, 2011b). It seems that having attained a certain level of wealth, people start to spend relatively more on culture, tourism, or higher quality objects, which does not necessarily lead to additional mineral resources being consumed. Another factor is that in the most developed countries, the main infrastructure (roads, railroads, electricity grid, etc.) is more or less in place and only needs to be maintained.

The estimates presented in the subsequent section are based on the mean of the results yielded by the two extraction growth scenarios described above.

4.3. Advances in technology

Thanks to continuous technological improvements to the mining and beneficiation processes, the recovery of mineral resources has become ever more cost-efficient and the real prices of most mineral resources have remained remarkably stable for a long period of time (Henckens et al., 2016b). If the real price of resources needs to be maintained at the 2020 level, this technological development must not be allowed to stop. However, the question is how long advances in technology can offset the price-increasing impact of lower grade ores and deeper mining in remoter and more environmentally sensitive places.

4.4. Exhaustion of mineral resources

Combining the data on the ultimately available resources (Table 2) with the extraction growth scenario explained in Section 4.2 and the extraction rates of mineral commodities for 2015 provided by the US Geological Survey yields the indicative exhaustion periods presented in Table 4 for thirty three mineral resources. Note that all three of my assumptions are somewhat optimistic. They are: (1) full decoupling of annual per capita consumption of all resources from growth in annual per capita GDP at some time in the foreseeable future, (2) a high estimate of the available resources and (3) stabilization of the world population at ten billion people. Hence the exhaustion periods obtained cannot be considered to be the result of a doom scenario.

The conclusions are as follows:

- One resource has an exhaustion period of 100 years: copper.
- Six resources have an exhaustion period of between 100 and 200 years: antimony, gold, boron, silver, bismuth, and molybdenum.
- Nine resources have an exhaustion period of between 200 and 1000 years: indium, chromium, zinc, nickel, tungsten, tin, rhenium, selenium, and cadmium.
- The other mineral resources considered have exhaustion periods of more than 1000 years.
- In the remainder of the article, the focus is on the thirteen scarcest mineral resources.

The next section estimates the effects of maximally increasing the recovery efficiency, substitution, material efficiency, and recycling of the scarcest resources, and of maximally decreasing their in-use dissipation and downcycling.

5. Opportunities for and limits of resource-saving measures

In this section it is investigated to what extent the extraction rate of the thirteen scarcest mineral resources identified in Section 4 can be reduced by implementing resource-saving measures. This will allow us to determine approximately how long scarce mineral resources will be available for future generations. If in reality the effectiveness of the resource-saving measures proves to be less or more than estimated in this article, the calculations presented in Section 6 will be overestimates or underestimates, and conclusions drawn will have to be revised accordingly.

Resource-saving measures will usually not be achieved without implementing adequate supporting policy measures. These measures could be (Henckens et al., 2019):

- Eco-labeling
- Sustainable purchasing
- Promotion of recycling-oriented design of products
- Subsidizing recycled scarce materials
- Prohibiting or taxing the disposal of products containing scarce mineral resources

Table 4
Indicative exhaustion periods of thirty-three extractable mineral resources (years after 2015). For details, see Supplementary Information (E). The three mineral resources with a negative growth between 1980 and 2015 have not been included in the Table.

Copper	100	Tungsten	600	Niobium	1700
Antimony	150	Tin	700	Arsenic	4500
Gold	150	Rhenium	700	Gallium	5100
Boron	150	Selenium	700	Rare Earth Elements	5300
Silver	150	Cadmium	850	Strontium	5400
Bismuth	150	Iron	1100	Aluminum	10,500
Molybdenum	200	Cobalt	1100	Titanium	24,000
Indium	250	Platinum Group Metals	1200	Tantalum	29,500
Chromium	350	Manganese	1350	Vanadium	40,000
Zinc	400	Lead	1500	Magnesium	40,000
Nickel	450	Lithium	1600	Germanium	550,000

- Scarce resource taxation
- Banning the use of certain applications of scarce mineral resources
- Establishing extraction quotas

Making the producers more accountable will undoubtedly help improve the effectiveness of these policy measures.

5.1. Potential for an increase in recovery efficiency

The recovery efficiency of a resource is the ratio of the actual extraction of a resource to the total amount of that resource contained in the mined ore. During beneficiation, the gangue is removed from the ore to produce a mineral concentrate. The waste (the tailings) comprises rock stripped of valuable minerals. In the subsequent processing of the concentrated ore, slag is produced: it is the glass-like by-product that remains after a metal has been separated from a smelted concentrated ore.

Table 5 shows the current recovery efficiency of thirteen scarce resources and also their feasible future recovery efficiencies as presented in Henckens (2021).

With regard to the potential for an increase of recovery efficiency three groups can be distinguished:

- No increase in recovery efficiency. The minerals in this group are antimony, boron, copper, gold, nickel, tin, and zinc. It seems that a further increase in their recovery efficiency is unlikely, because they already have a high recovery efficiency of $>$ 80%. Given that, in general, ore grades will decrease, more energy will be needed for the beneficiation process. The higher the current recovery efficiency, the more energy will be required to increase that efficiency.
- A small increase in recovery efficiency, to 80%. This seems feasible in the future for chromium, silver, and tungsten. In all three, this entails improving recovery efficiency by less than 10%.
- The final group comprises bismuth, indium, and molybdenum. Because they have relatively high companionality,[1] their present recovery efficiency is relatively low (bismuth: 60%, indium: 35% and molybdenum: 60%). However, recovery efficiencies are deemed to potentially increase to 70% in the case of bismuth and indium, and to 80% for molybdenum. The current recovery efficiency of indium is still low, but according to Werner et al. (2015), indium production per unit of zinc increased sixfold in the period 1988 to 2012. Currently, about 60% of molybdenum is a by-product of copper production with a recovery efficiency of about 45%, while 40% of molybdenum is produced from molybdenum mines with an estimated molybdenum recovery efficiency of about 80% (Henckens et al., 2018).

Table 5
Recovery efficiency of thirteen scarce mineral resources now and in the future.

	Current recovery efficiency at the mining stage	Source	Maximum future recovery efficiency[a]
Antimony	94%	Anderson (2012)	94%
Bismuth	60%	Krenev et al. (2015); Chen et al. (2012); Ha et al. (2015)	70%
Boron	95%	Özdemir and Kipçak (2010), Boncukcuoğlu et al. (2003)	95%
Chromium	74%	Johnson et al. (2006)	80%
Copper	84%	Glöser et al. (2013), Lifset et al. (2002)	84%
Gold	90%	Hylander et al. (2007)	90%
Indium	35%	Licht et al. (2015); Werner et al. (2015)	70%
Molybdenum	60%	Henckens et al. (2018)	80%
Nickel	82%	Reck et al. (2008)	82%
Silver	73%	Johnson et al. (2005)	80%
Tin	89%	Izard and Müller (2010)	89%
Tungsten	75%	Leal-Ayala et al. (2015)	80%
Zinc	81%	Meylan and Reck (2016)	81%

[a] Source: Henckens, (2021).

[1] The companionality of a material is the proportion of that material that is produced as a by-product of the extraction of another (host) material

The last group of resources (bismuth, indium, molybdenum) is the only one in which increasing the recovery efficiency plays a significant role in making the use of the resource more sustainable.

5.2. Substitution

The substitutability of a material is determined by four factors (Henckens et al., 2015)

- The substitute's performance compared with the performance of the original.
- The substitute's environment, health, and safety (EHS) properties compared with the EHS properties of the original.
- The costs of the substitute compared with the costs of the original.
- The substitute's geologic availability compared with the geologic availability of the original.

In some cases, an application is so specific that substitution is difficult or impossible.

Table 6 presents the substitutability of the thirteen scarce raw materials considered. It shows that only four (antimony, boron, indium, and zinc) have a substitutability of 50% or more, three (bismuth, tin, and tungsten) have a substitutability between 10% and 50%, and the remaining six (chromium, copper, gold, molybdenum, nickel and silver) have a substitutability of 10% or less. For the latter six resources, substitution will not play a major role in making their use more sustainable.

Table 6
Substitutability of thirteen scarce materials.

	Substitutability	Source
Antimony	90%	Henckens et al. (2016a)
Bismuth	35%	Henckens (2021), US Geological Survey (2019a)
Boron	57%	Henckens (2021), Faruk et al. (2014), Jelle (2011), Lopez et al. (2012a and 2012b), Papadopoulos (2005), US Geological Survey (2019b), European Commission (2010), Risk and Policy Analysts (2008)
Chromium	0%	US Geological Survey (2020d), Oakdene Hollins Fraunhofer (2013), Johnson et al. (2006)
Copper	10%	Henckens (2021), US Geological Survey (2018b), Ayres et al. (2002)
Gold	0%[a]	Henckens (2021).
Indium	50%	Henckens (2021), US Geological Survey (2020a), Ylä-Mella and Pongracz (2016), Chen and Graedel (2012), European Commission 2013
Molybdenum	10%	Henckens (2021), US Geological Survey (2017a), Oakdene Hollins and Fraunhofer (2013)
Nickel	0%	US Geological Survey (2018a), European Commission (2014), British Geological Survey (2008)
Silver	10%	Henckens (2021), Butterman and Hilliard (2004)
Tin	40%	Henckens (2021), US Geological Survey (2020e)
Tungsten	30%	Henckens (2021), US Geological Survey (2020b), European Commission (2013)
Zinc	70%	Henckens (2021), US Geological Survey (2020c), Oakdene Hollins Fraunhofer (2013), Roovaart and Van Duijnhoven (2007), Annema and Ros (1994)

[a] Refers only to technological applications of gold.

5.3. Increasing the material efficiency

Material efficiency (or resource productivity) reflects the quantity of services that a given amount of a material can provide: lightweighting of packaging may result in less material being used to package the same amount of product. Ways in which material efficiency can be improved include longer use of a product, shared use of a product, reuse of a product, lighter products. Decreasing in-use dissipation, downcycling, and disposal are part of material efficiency improvement, but are considered separately in this paper.

The material efficiency improvement potential indicates the percentage by which the use of a material can be reduced while still providing the same quantity of services. Thus, if a material has a material efficiency potential of 25%, only 75% of the original quantity of that material would be needed to ensure the service level is maintained. In general, the estimated material efficiency improvement potential (excluding reducing in-use dissipation and increasing the end-of-life recycling rate) varies between 1% and 50% (Henckens et al., 2015).

Extending the product lifetime results in larger in-use stocks of mineral resources and, initially, to less recycled material. A longer product lifetime is not always beneficial: greenhouse gas emissions from old products that are kept and used for a long time may be much greater than the emissions from new or alternative products. This is the case for the long use of old diesel cars, coal-fired power stations, old refrigerators, and filament light bulbs. Moreover, long use may hamper the development and use of products that are more environmentally and climate friendly.

In this article, a default material efficiency potential of 10% has been assumed for all mineral resources considered. This does not include the impact of dissipation reduction and increased recycling of materials from end-of-life products.

5.4. Decreasing the in-use dissipation

In-use dissipation is the loss of a resource to the environment through and during its consumption, e.g., by corrosion, or by using the resource in a fertilizer. In-use dissipation of a raw material occurs in a range of applications, such as in food, fertilizers, detergents, chemicals, paints, lubricating oil, and anti-corrosives. Some mineral resources have a substantial in-use dissipation, others have little or none. Sometimes it is possible to substitute the material with another material—or to use less of it, e.g., in detergent, paint, lubricating oil, or anti-corrosives. Sometimes this is not possible, such as when an element is applied in food or as a micronutrient.

Table 7 presents both the current in-use dissipation of the thirteen scarce resources considered and the potential reduced dissipation rates, both as estimated by the author.

The in-use dissipation of most resources is low. However, some resources (bismuth, boron, molybdenum, and zinc) have a relatively high in-use dissipation rate due to their use in chemicals, pharmaceuticals, detergents, etc. In most cases it will hardly be possible to reduce the dissipation rate without having to substitute the material used in the application. An exception to this rule is zinc's application in galvanizing. Galvanized surfaces can be protected by a plastic coating which can substantially reduce zinc dissipation to the environment. A major source of the in-use dissipation of tungsten is the use of tungsten carbide products in abrasive applications. It should be possible to decrease this to such an extent that the overall in-use dissipation of tungsten can be reduced from 3% to 2%.

5.5. Decreasing the downcycling

Downcycling is the phenomenon whereby an element is recycled together with another element and loses its specific functions while permanently included in the flow of the other element. In effect, downcycling is disposal in a way that is not via landfills or incinerators.

Table 7
Current in-use dissipation and potential in-use dissipation, assuming that applications or their distribution remain the same as in 2020 and there is no substitution.

	Current in-use dissipation (% of consumption)[a]	Dissipative uses and processes	Potential in-use dissipation rate[a]
Antimony	1%	Pigments, lubricants, fireworks, matches	1%
Bismuth	35%	Pharmaceuticals, cosmetics, chemicals	35%
Boron	35%	Fertilizer, detergents, chemicals, cosmetics	35%
Chromium	0%		0%
Copper	2%	Micronutrients, corrosion, chemicals	2%
Gold	0%		0%
Indium	0%		0%
Molybdenum	8%	Chemicals	8%
Nickel	0%		0%
Silver	0%		0%
Tin	0%		0%
Tungsten	3%	Abrasion, erosion, and chemicals	2%
Zinc	8%	Biocides, lubricants, pig feed additives, corrosion of galvanized products	5%

[a] Source: Henckens, (2021).

It is very difficult to reuse a downcycled element in a functional way. Stainless steel contains a variety of metals in a mix that varies depending on the type of stainless steel. The extent to which different types of steel are separated from each other at the end-of-life stage depends on whether separation is economic: thus, metal A's market price and its concentration in steel B will determine whether and to what extent it is financially attractive to keep steel B separate from other types of steel in order to recycle steel B in its original application together with metal A rather than to recycle steel B together with a number of other types of steel in which metal A has no specific function. Table 8 presents the current downcycling rates and the potential decrease in downcycling rate for the thirteen scarce mineral resources.

The downcycling rates of the different scarce raw materials considered are clearly very divergent. The highest downcycling rates are those of applications in steel, lead, and other alloys. The lower the concentration of a resource in an application, the less economic it is to recycle that resource in order to make it available for its original functions.

Downcycling, disposal, and recycling are interrelated: in general, a decrease of downcycling leads to a proportional increase of recycling. The estimates in Table 8, and explained in the below text, are derived from Henckens (2021).

Antimony. 70% of antimony in lead alloys is currently downcycled. A reduction of the downcycling rate to 35% is deemed feasible in the future.

Chromium. Daigo et al. (2010) report that the recycling rate of chromium from austenitic stainless steel is more than 75%, whereas the recycling of chromium from ferritic stainless steel is less than 40%. Nakamura et al. (2017) report that a sorting process that separates carbon steel from stainless steel and other alloy steels from carbon steels is able to retain more than 70% of chromium and nickel for functional use. More selective sorting of stainless steel and other chromium-containing alloy steels from a scrap mix will keep stainless steel out of the carbon steel cycle. It is estimated that doing so would make it possible to reduce downcycling of chromium by about 50%.

Copper. A small proportion of copper is downcycled to the iron and steel loop. It is deemed feasible to reduce copper downcycling by 50% as a result of improved separation and sorting of copper-containing end-of-life products.

Molybdenum. About 60% of molybdenum use is to manufacture grade

Table 8
Current downcycling rates of the thirteen scarce mineral resources and the potential reduction of downcycling, assuming that applications or their distribution remain the same as in 2020.

	Current downcycling (% of end-of life products plus industrial waste)	Main applications involved	Source	Potential downcycling rate (Henckens, 2021)
Antimony	8%	Lead alloys	Henckens, 2021	4%
Bismuth	0%		Henckens, 2021	0%
Boron	0%		Henckens, 2021	0%
Chromium	35%	Different types of steel	Johnson et al., 2006	17%
Copper	4%	Cars and large domestic appliances	Ruhrberg, 2006	2%
Gold	0%		Henckens, 2021	0%
Indium	4%	Architectural glass, dental applications	Licht et al., 2015	4%
Molybdenum	50%	Different types of steel	Henckens, 2021	20%
Nickel	14%	Different types of steel and alloys	Reck et al., 2008	10%
Silver	0%		Henckens, 2021	0%
Tin	16%	Cans and containers	Izard and Müller, 2010	5%
Tungsten	20%	Different types of steel	Leal-Ayala et al., 2015	10%
Zinc	0%		Henckens, 2021	0%

alloy steel and iron, where it is applied in concentrations of between only 0.2% and 0.5%. Most of these alloys are recycled for the purpose of steel recycling, leading to an overall downcycling of about 50% of molybdenum. It is easier to recycle molybdenum from its applications in stainless steels and molybdenum metal and super alloys, because although they account for only about 30% of molybdenum's applications, they contain much higher concentrations of molybdenum. Molybdenum-oriented recycling from its applications in grade alloy steel and iron is complex and will require a major restructuring of iron and steel recycling. Nevertheless, a reduction by 50% of the current molybdenum downcycling from its applications in grade alloy steel and iron is deemed feasible in the future. Among other things, this will entail more selective dismantling of products containing molybdenum, more plans for molybdenum-oriented steel scrap blending, and better scrap sorting–e.g., by application of Laser Induced Breakdown Spectroscopy (Gurell et al., 2012).

Nickel. Nickel is a minor constituent of low alloy steels and in plating, so it is not yet economically attractive to include these products in the nickel cycle. Such products make up about 14% of total nickel scrap (Reck et al., 2008). Via this scrap, nickel becomes a constituent of carbon steel or copper scrap cycles and is downcycled. My calculations reveal that increasing the fraction of separately collected end-of-life products that contain nickel would make it feasible to reduce nickel downcycling by one third.

Tin. According to Izard and Müller (2010), in 2005, about 65% of tin in plated cans and containers in the USA was downcycled to the steel cycle. About 25% of tin is used in cans and containers. Tin can technically be recycled from tinplated cans by detinning end-of-life cans before recycling them to the steel cycle. This has historical precedent but is currently unprofitable. According to Henckens (2021), a two-thirds recycling of the tin from cans is feasible and would reduce downcycling of tin from 16% to 5%.

Tungsten. Steels with a relatively low tungsten content are currently recycled in the steel cycle. The tungsten contained is lost for specific tungsten applications. This concerned about 20% of tungsten applications in 2010 (Leal-Ayala et al., 2015). Like other metals, a better sorting of different alloys in the future will enable more of the material to be recycled and less to be downcycled. Henckens (2021) estimates that in this way, downcycling of tungsten could be halved.

Zinc. Zinc shows no downcycling, because it vaporizes in the steel or copper melting furnaces. The resulting zinc-containing dust is recycled or disposed of. Other metals, such as chromium, molybdenum, and tungsten remain in the liquid phase of the melt together with the main metal (iron/steel, lead, or aluminum).

5.6. Increasing the recycling

The recycling potential of a specific material from a specific product depends on the following factors (Graedel and Erdmann, 2012; Worrell and Reuter, 2014):

- *Concentration.* The higher the concentration, the higher the recycling potential. As a general rule, the concentration should be at least as high as the minimally profitable concentration in virgin ore.
- *Material composition.* Alloys, composites, and laminates of various materials make it difficult to isolate the mono-materials, which may limit (or even inhibit) recycling or result in downcycling.
- *Product composition.* The more complex the composition or assemblage of the product, the lower the recycling potential.
- *Dissipative uses.* Dispersed or dissipative use of materials inhibits the economic recoverability of materials.
- *Contamination.* The more contaminated a waste product is, the lower the recycling potential.

Recycling rates higher than 85–90% are not feasible in practice because there will be losses at every step of the recycling chain (collection, sorting, processing). Moreover, it can be costly to recycle a material from a product because of a low concentration, or a complex product composition. To enable a high recycling rate of a specific material, an infrastructure needs to be created that includes many stakeholders (e.g., manufacturers, households, waste management companies, recycling traders and processors, local governments) and that encompasses the generation of new national or international markets for recycled material. Building such an infrastructure is capital- and time-intensive and is affected by changes in product and material compositions. Yet recycling is a core element of primary resource use reduction and material efficiency. It will always be part of the portfolio of measures aiming to reduce primary resources use sufficiently.

Table 9 presents the current end-of-life recycling rates of the thirteen scarce mineral resources considered, together with estimates of their potential recycling rates. The potential end-of-life recycling rates are explained in more detail in Supplementary Information (A).

Only three of the thirteen scarce mineral resources currently have an end-of-life recycling rate of 50% or more: gold, silver, and nickel. For three others (bismuth, boron, indium), nothing is recycled from end-of-life products.

The end-of-life recycling rate of all thirteen resources can be substantially increased. However, it will be difficult to increase the end-of-life recycling rates for boron, indium, and tin to more than 50%. Boron's end-of-life recycling rate in particular is expected to remain low, because of the relatively high rate of dissipative use and the limited recyclability of boron's other applications.

Table 9
Current end-of life recycling rates and potential increase of end-of-life recycling rates for thirteen scarce mineral resources, assuming no change in their applications. See Supplementary Information (A).

	Current global end-of-life recycling rate	Sources	Potential global end-of-life recycling rate[a]
Antimony	20%	Thiele (2009), Henckens (2021), Carlin (2006)	55%
Bismuth	0%	US Geological Survey (2019a)	48%
Boron	0%	US Geological Survey (2019b)	14%
Chromium	34%	Henckens (2021), Johnson et al. (2006)	70%
Copper	45%	Henckens (2021)	70%
Gold	86%	Henckens (2021)	91%
Indium	0%	Licht et al. (2015)	38%
Molybdenum	20%	Henckens (2021)	50%
Nickel	57%	Reck et al. (2008)	70%
Silver	50%	Henckens (2021)	65%
Tin	21%	Henckens (2021), International Tin Association (2020)	40%
Tungsten	30%	International Tungsten Industry Association (2018)	60%
Zinc	33%	Meylan and Reck (2016)	70%

[a] Henckens, (2021), see Supplementary Information (A).

6. Results of taking maximum saving measures for extraction reduction and exhaustion delay

Below it is estimated how long the scarcest resources might be available for humanity if measures are taken to decrease their extraction rate as much as possible while simultaneously achieving a service level in all countries that is the same as the service level in developed countries in 2020 and assuming a world population of ten billion people. The first step is to determine the potential decrease in extraction under the following conditions: maximum recovery efficiency, maximum substitution, a material efficiency improvement of 10%, minimum dissipation of remaining material, and maximum end-of-life recycling of the remaining material. The calculation is based on the data from Section 4. The results are presented in Table 10. Details are provided in Supplementary Information (B).

Table 11 presents the indicative exhaustion periods after applying the maximum resource-saving measures as described in Section 5 and assuming a world population of ten billion people enjoying the same service level as experienced by inhabitants of developed countries in 2020. Details are presented in the Supplementary Information (C).

The conclusions are as follows.

Table 10
Maximum possible reduction of the extraction of thirteen mineral resources, obtained by taking maximum resource-saving measures while simultaneously achieving a service level in all countries that is the same as that in developed countries in 2020, assuming current technology. See Supplementary Information (B).

Maximum decrease in extraction		Maximum decrease in extraction	
Antimony	95%	Molybdenum	64%
Bismuth	75%	Nickel	65%
Boron	65%	Silver	70%
Chromium	71%	Tin	61%
Copper	68%	Tungsten	68%
Gold	86%	Zinc	87%
Indium	89%		
Mean maximum decrease in extraction			74%

Table 11
Indicative exhaustion periods assuming maximum measures are implemented and a world population of ten billion enjoys the same service level as developed countries in 2020. See Supplementary Information (C).

	Exhaustion periods without measures (years, Table 4)	Exhaustion period after maximum measures, assuming a world population of ten billion people with the same service level as developed countries in 2020 (years, rounded)	Delay expressed as the ratio of the exhaustion period after maximum measures to the exhaustion period without measures
Antimony	150	3000	20
Bismuth	150	900	6
Boron	150	1000	6.7
Chromium	350	2000	5.7
Copper	100	300	3
Gold	150	800	5.3
Indium	250	70,000	280
Molybdenum	200	400	2
Nickel	450	2000	4.4
Silver	150	500	3.3
Tin	700	500	0.7
Tungsten	600	1000	1.7
Zinc	400	3000	7.5

- For four of the thirteen scarce mineral resources (copper, molybdenum, silver, and tin), implementing the maximum measures delays exhaustion by no more than 350 years, resulting in the new exhaustion period being no more than 500 years. For tin, the exhaustion period even shows a decrease after maximum measures, which is counterintuitive but is due to the different points of departure for calculating the exhaustion period without measures and the exhaustion period with maximum measures. The calculation of the exhaustion period with maximum measures assumes a simultaneous and immediate increase in the worldwide consumption of the resource to the level of developed countries in 2020, i.e., a quadrupling of consumption. In the calculation of the exhaustion period without measures for tin, a quadrupling of the consumption level is only reached after 600 years, because the increase in tin extraction is not exponential but linear (1.5 kt/year). See Henckens (2021).
- For the remaining nine scarce mineral resources, implementing maximum resource-saving measures leads to delays of >400 years, resulting in exhaustion periods of > 800 years.
- Antimony and indium show a very large increase in exhaustion period if maximum measures are taken. In the case of antimony, this is mainly because of the high substitution potential. In the case of indium, this is because the original exhaustion period of 250 years is based on a very high temporary increase in extraction: the 8.1% per annum increase between 1980 and 2015 resulted in annual extraction doubling every ten years. In the calculation of the exhaustion period with maximum measures, it is assumed that the global per capita consumption level increases immediately to the level of developed countries in 2020. For indium, this increase is indeed by about a factor of four, but under the scenario without measures, the same increase in extraction would be reached within only twenty years and would continue increasing rapidly thereafter, resulting in a relatively short exhaustion period.
- For eleven of the thirteen mineral resources considered, exhaustion is delayed by between a factor of one and a factor of seven, and is on average a factor of about four.
- Hence the overall conclusion is that taking maximum measures to save mineral resources would make it possible to increase the worldwide service level by an average of a factor of four to achieve the level enjoyed in the developed countries in 2020. Simultaneously, extraction could be decreased by about a factor of four, meaning that exhaustion of most of these mineral resources could

also be delayed by a factor of four–assuming that the world population stabilizes at ten billion people.

Table 12 provides an overview of the potential impact of the maximum measures for each of the thirteen mineral resources.

Hence, the conclusion is that to achieve maximum reduction of the extraction of the thirteen scarce mineral resources, the following measures have an important impact:

- Substitution, for antimony, bismuth, boron, indium, tin, tungsten, and zinc
- Recycling, for all thirteen resources but less for antimony and boron
- Increase of recovery efficiency for indium and molybdenum

7. Sensitivity analysis

Many of the assumptions underlying the calculations are somewhat optimistic. Table 13 shows the impact of making five important assumptions less optimistic.

Economic growth in the word is partly due to an increasing GDP per citizen, and for another part by an increase of the population. Therefore, a higher growth scenario (row 3) overlaps with a higher world population (row 4). This would lead to double counting in the sensitivity analysis. Taking this into account, the overall conclusion from the sensitivity analysis can nevertheless be that the cumulative effect of the more pessimistic assumptions included in column 3 is very substantial. The exhaustion periods of the mineral resources presented in the middle column of Table 11 may shrink by as much as 90%. This analysis shows the urgency of taking resource-saving measures.

Table 13
Sensitivity analysis.

–	1	2	3	4
	Aspect	Assumption in this article	Less optimistic assumption for the purpose of the sensitivity analysis	Impact of less optimistic assumptions
1	Available resources	The highest amount of two approaches	The average amount of two approaches	30% reduction in assumed available resources
2	Mining depth	3 km	2 km	33% reduction in assumed available resources
3	Growth scenario	The average of two growth scenarios	The scenario with the highest growth	Exhaustion is 40% faster
4	World population	10 billion	15 billion	Demand is 50% higher than assumed in the article
5	Resource-saving measures	See Section 5	30% less resource saving than assumed in this article	Decrease in global per capita demand for primary resources averages about 50% instead of 75%

8. Conclusions

8.1. Conclusions

This article has explored how the extraction rate of thirteen scarce raw materials can be made more sustainable. "*More sustainable*" means making the resource available worldwide at the same level as in developed countries in 2020 (intragenerational equity) while also prolonging its availability for future generations (intergenerational equity). The thirteen scarce raw materials considered were antimony, bismuth, boron, chromium, copper, gold, indium, molybdenum, nickel, silver, tin, tungsten, and zinc. It was investigated to what extent their extraction could be limited by increasing the recovery efficiency at the mining stage, by substitution, by improving material efficiency, by reducing dissipation, and by increasing of recycling, while keeping the services of the resource at the same level. It was found that at constant service level, extraction can be decreased by between 61% and 95%, with the average being 74%.

The overall conclusion is that if maximum resource-saving measures are implemented, it would be feasible to increase the worldwide service level of the thirteen scarce mineral resources by a factor of four to achieve the same service level as that enjoyed in 2020 by people in developed countries, while simultaneously also prolonging the time that these resources are available for next generations by a factor of between 0.7 and 7.5, with an average of about 4. This excludes antimony and indium. The exhaustion period of antimony can be extended by a factor 20, because of the very high substitution potential of antimony. The

Table 12
Overview of the potential of the maximum measures for thirteen scarce mineral resources. The shading indicates the measures with the relatively largest impact on the decrease in extraction.

Element	Potential increase in recovery efficiency (%)	Substitutability (%)	Material efficiency potential (%)	Potential reduction in dissipation of the remaining applications (%)	Potential increase in end-of-life recycling of the remaining applications (%)	Remarks
Antimony	–	90	10	–	20 →50	
Bismuth	60 →70	35	10	35 →0	0 →50	Dissipation of bismuth becomes zero, because the dissipative dissipative bismuth applications are all substituted sub
Boron	–	57	10	35 →50	0 →21	Dissipation of boron increases because, after substitution, a larger proportion of the remaining boron applications are dissipative
Chromium	74 →80	–	10	–	35 →70	Recycling of chromium includes end-of-life products and industrial waste
Copper	–	10	10	2 →1	45 →70	
Gold	–	–	10	–	60 →87	
Indium	35 →70	50	10	–	0 →50	
Molybdenum	60 →80	10	10	-	20 →50	
Nickel	–	–	10	–	57 →70	
Silver	73 →80	10	10	–	50 →70	
Tin	–	40	10	–	21 →40	
Tungsten	75 →80	30	10	3 →2	30 →60	
Zinc	–	70	10	–	33 →64	

exhaustion period of indium can even be extended by a factor 280, because of the supposed very high annual extraction rate growth of indium of more than 8%, based on the annual growth figures between 1980 and 2015.

As the results are based upon optimistic estimates and assumptions about the available amounts of extractable resources in the Earth's crust, worldwide economic growth, future world population, and the feasibility of the assumed resource-saving measures, they need to be considered as optimistic as well. A sensitivity analysis shows the impact of less optimistic assumptions. The approach used in this article can be used to revise the results as new data become available.

CRediT Author Statement

MLCM Henckens: conceptualization, methodology, writing original draft, visualization.

J.Burrough: Writing-review & editing.

Supplementary Information

In the Supplementary Information details are provided on:

(A) Current and future end-of-life recycling rates of the thirteen scarce mineral resources

(B) The potential reduction of the extraction of the thirteen scarce mineral resources when maximum resource-saving measures are applied

(C) Indicative exhaustion periods

(D) Estimates of the ultimately available resources

(E) Exhaustion periods of elements under two different scenarios

(F) Estimated per capita consumption of resources in developed countries in 2020

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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