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Mineral resources governance: A call for the establishment of an International Competence Center on Mineral Resources Management

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ABSTRACT

Non-renewable resources must be used as economically as possible, to prevent their rapid exhaustion and ensure they benefit all humankind and future generations. Yet, in this paper we make plausible that several mineral resources may be depleted within the next 100 years unless effective policies help reduce extraction to more sustainable levels. In this paper, we investigate eleven policy instruments that could advance the sustainable use of antimony, boron, gold, molybdenum, and rhenium. We conclude that gold and rhenium do not require a specific approach. Their market price is so high and their recycling from most products so rewarding that little of them is dissipated in the environment, or disposed of in landfills. Almost all extracted gold and rhenium remains available for use. This market effect does not apply to antimony, boron, and molybdenum. Our assessment is that the most effective measure for achieving a more sustainable extraction rate for these three materials is to establish global extraction quotas. However, the necessary international agreement involves many interests and will take much time to be achieved. Moving toward more sustainable use of these metals requires other policy instruments (e.g., banning certain applications from the market; promoting or obliging recycling-oriented product design; imposing levies on scarce resources; subsidizing recycled material; and imposing levies or prohibiting disposal of products in landfills). A precondition for successful global mineral resources governance is the establishment of an International Competence Center on Mineral Resources Management.

1. Introduction, background, and approach

A mineral resource is "*a concentration of naturally occurring […] material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible*" (USGS (2018a)). For over a century, the extraction of mineral resources has increased exponentially by 2–6% annually (USGS, 2017a) due to increasing world population and rising Gross Domestic Product per capita. The depletion rate of a mineral resource depends on the ratio of the ultimately extractable resources on the one hand and the future annual extraction on the other hand. Although the total occurrence of elements in the Earth's crust is enormous, and quasi-unlimited, most of this cannot be economically extracted. A mineral becomes a mineral resource only, when its concentration and accessibility are such that extraction is economically and environmentally justified. The threshold is not absolute. Thus far, ever lower concentrations have been extracted at ever greater depths and ever remoter places. The more the consumer is prepared to pay, the lower the concentrations that can be extracted and the deeper the mining can take place. Gold is extracted to much lower concentrations and in much less accessible places than iron. From a technical point of view, a mineral can be extracted from the Earth's crust to a very low concentration, but in practice this will never happen. From a certain point on, extraction becomes economically senseless. This is for instance the case, if the energy requirements for copper extraction become so high that the amount of copper needed for the copper production is bigger than the amount of copper that is produced. But in practice the limit will be reached much earlier, not only due to economic reasons, but also due to the impacts of the extraction on climate and environment because of the very high energy requirements of extraction and the enormous amounts of waste produced and water needed. Generally, the ultimate extractability of a mineral resource is limited to a larger extent by economic, environmental, climatic and social restrictions than by the mere availability of the resource. Regarding this issue it is referred to the papers of Mudd et al (2007, 2008, 2009, 2010, 2017a, 2017b). Several scholars have tried to estimate the limits to the extractable amounts of mineral resources. In the scientific literature we identified four different types of approaches for estimating the ultimately extractable resources: (1) the approach based upon the assumption that the ultimately extractable amount of a resource is proportional to the average crustal abundance

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of that resource (Rankin, 2011; UNEP, 2011; Skinner, 1976; Graedel and Nassar, 2015; Mookherjee and Panigrahi (1994); Nishiyama and Adachi, 1995; Erickson, 1973); (2) the approach based on the relationship between the results of a thorough and recent assessment of the amount of extractable resources of a number of minerals in the United States and the amount of the same resources as identified by USGS worldwide (our own approach, see the Supplementary Information); (3) the approach based on the so-called tectonic diffusion model as developed by Kesler and Wilkinson (2008); (4) the approach based on research on the available resources of specific materials, e.g. by Mudd et al. (2013); Mudd and Jowitt (2014); Mudd et al. (2017c); Mudd and Jowitt (2018a) and Mudd et al. (2018b) on respectively cobalt, nickel, lead, copper & zinc and Platinum Group Metals, by Jowitt and Mudd (2014) on gold, by Mohr et al (2012) on lithium, by Singer (2017) on copper, by Sverdrup et al (2014 a, 2014 b, 2015, 2016a, 2016b) on respectively copper, silver, aluminium, lithium, and Platinum Group Metals, by Weng et al (2015) on Rare Earth Elements. The results of these four approaches are presented in the Supplementary Information. On the basis of the results of these four approaches we estimate that the extractable amounts of the following materials may be exhausted within a century: gold, copper, silver, antimony, bismuth, boron, rhenium, molybdenum, and nickel (for more details, see the Supplementary Information to this paper). Exhaustion of a mineral resource has serious economic consequences for future generations, including a permanent, very high cost increase of the mineral resource in question. Exhaustion is the irreversible effect of careless and unrestricted use of scarce mineral resources. Exhaustion does not mean that there is nothing of the material left in the Earth's crust anymore. Exhaustion means that extraction of the material is no longer profitable due to an accumulation of economic, environmental, climatic and social reasons. Further extraction would cost more than it would produce. Like climate change and loss of biodiversity, its impact will be felt in the longer term, not immediately. Therefore, confronted with other pressing global problems, humanity may not realize the urgent need to act now to address the future exhaustion of certain mineral resources.

There are warnings about the future exhaustion of some mineral resources (e.g. Rankin, 2011; UNEP, 2011; Erickson, 1973; Nickless, 2017; Ragnarsdottir et al., 2012; Sverdrup et al., 2017). However, thus far, technological development in combination with expansion of brownfields and better knowledge on ore forming systems have been able to neutralize the increasing costs of extracting lower-grade ores, deeper mines, and remoter mine locations fully or for a substantial part. The Escondida copper mine in Chile and the Grasberg copper mine in Indonesia are examples of large brownfield expansions. Consequently, market prices of almost all minerals have remained remarkably stable in real terms (USGS, 2017a). Henckens et al. (2016b) demonstrated that so far the long-term geological scarcity of a resource has not significantly influenced its price trend. We believe this is because the time horizon of market prices of mineral resources is some years to some decades at most and the maximum forward time for futures on the London Metal Exchange is about ten years. Mining companies look ahead a maximum of 20–30 years, because exploration is expensive. The cost per discovery between 1975 and 2010 in Australia were about 50–60 million 2015 US Dollar (Schodde, 2015). Thus the market price of a mineral resource might only react when that resource is almost exhausted. The free market price mechanism reacts to today's and tomorrow's developments but does not necessarily take account of the interests of future generations, which are still at least decades ahead.

To overcome this limitation of the market, the governance of mineral resources and mineral resources policy at a global scale need to be improved and implemented more effectively very soon to anticipate the future exhaustion of scarce mineral resources. By exhaustion of a mineral resource we mean a lack of profitability or feasibility of further extraction of that resource due to (a combination of) financial, environment, energy, climate change, waste, water use, and social factors. We define mineral resources governance as the set of norms, values, and rules through which mineral resources are managed. Despite general intentions[1], at global level international mineral resources governance and international mineral resources policy are practically nonexistent, although they exist on a country-by-country basis like in Australia[2]. We define mineral resources policy as a set of concrete goals for achieving a more sustainable use of mineral resources in the interests of future generations.

The main technical measures for reducing the use of a mineral resource are the substitution of the resource by a less scarce material, a higher recycling rate from end-of-life products, improvements in material efficiency, and measures to limit dissipation of the resource during its use. Furthermore, technological developments and governmental limitations may change the demand, e.g. the banning of the use of lead in gasoline, the decrease of the (future) use of Platinum Group Metals in catalytic converters due to the transition to the use of electric cars, the lesser use of cadmium in certain products due to its toxic characteristics. However, none of these will happen spontaneously. To be widely used, substitutes must be cheaper than the original. Normally, recycling must be cheaper than using the primary resource from the mine[3]. Higher material efficiency must be rewarded. Thus, to ensure mineral resources policy results in the available technical reduction options being implemented, dedicated instruments are essential.

In response to impending resource exhaustion or scarcity, various authors (e.g., Sverdrup et al., 2017; Valero and Valero; 2010; Calvo et al.; 2016; Ali et al., 2017; Christmann, 2017; Tilton et al., 2018) have advocated developing international resources policies. The effectiveness of policy instruments will depend on the specific characteristics of the scarce material, e.g. substitutability, recyclability, and applications. To investigate this we selected five scarce materials: antimony, boron, gold, molybdenum, and rhenium, chosen because they differ from each other in terms of market price, substitutability, and recyclability.

In this paper we analyze and assess eleven different policy instruments for achieving a more sustainable use of the five materials. In Section 2 we analyze the impact of market price, substitutability, and recyclability on the applicability of technical measures for reducing their consumption. In Section 3, we analyze and assess eleven policy instruments for achieving a more sustainable extraction rate of scarce mineral resources. Our conclusions and a discussion on the results are presented in Section 4. The selection of the policy instruments and their assessment are based on detailed analysis of primary and secondary

[1] Already in 1972, the world's nations stated that *"the non-renewable resources of the earth must be employed in such a way as to guard against the danger of their future exhaustion"* (Principle 5 in the Declaration of the United Nations Conference on the Human Environment in Stockholm, 1972). More recently, the report on the "*Implementation of Agenda 21 on Sustainable Development Goals*" declares as target 12.2: "*By 2030 achieve the sustainable management and efficient use of natural resources*" (United United Nations, 2015).

[2] Several countries and also the European Union have developed policies regarding raw materials that are critical for their economies. In the approach of the European Union, criticality of a material is determined by two factors: the economic importance of a material for the member countries and the supply risk of the material. The economic importance is determined by the applications of the material and the EU mega sector value. The supply risk is determined by the substitutability of the material, the recycling rate, the country concentration of supply (few or many suppliers) and governance quality of the supplying countries. Geological scarcity and potential exhaustion are not part of this system. It is referred to http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en on EU's critical raw materials policy.

[3] Recycling can also be triggered by the imbalance between offer and demand. E.g. currently the demand for dysprosium and neodymium, two Rare Earth Elements, is high compared to the demand for other Rare Earth Elements. Adjusting the total REE production to the highest demand of any REE would be an expensive solution and would necessitate stockpiling of REEs in lower demand. This makes recycling of dysprosium and neodymium from end-of-life consumer goods interesting (Binnemans et al., 2013).

Table 1
Market prices of five scarce mineral resources (1998 US$ per kg in the USA) (USGS, 2017a).

Element	Year					
	1990	1995	2000	2005	2010	2015
Gold	15.500	13.300	8.530	11.900	29.500	25.700
Rhenium	1.410	749	825	868	3.530	1.860
Molybdenum	7.84	18.60	5.33	58.50	26.00	9.97
Antimony	2.25	5.38	1.36	2.95	6.61	4.95
Boron	0.898	0.797	0.891	0.780	0.508	0.345

sources from the scientific literature.

2. Market price, substitutability, and recyclability

Three factors impact greatly on the applicability of technical measures for reducing the use of scarce mineral resources and on the effectiveness of different policy instruments: the raw material's market price, its substitutability, and its recyclability. This is underpinned in the below paragraphs.

2.1. Market price

The higher the market price of a resource, the greater the market pressure to substitute the mineral, to recycle it, or to abandon it, and the less need there is for governments to act to reduce its global extraction. Current market prices of gold and rhenium are much higher than those of antimony, molybdenum and boron (Table 1). The high market price incentivizes substitution and recycling of even small amounts of gold and rhenium, implying that gold and rhenium will need specific policies to reduce their use to a lesser extent than antimony, molybdenum and boron. We expect that the free market price mechanism will automatically lead to their thrifty use and to maximizing their recovery from end-of-life products. We refer to Table 3 in this section on the present recycling rate of the five materials mentioned in Table 1, showing that, for these materials, their recycling rate is higher to the extent that their market price is higher. Of course, actual recycling and substitution will also depend on the feasibility of recycling and substitution. From certain applications, it will be difficult (meaning relatively expensive) to recycle elements, such as for instance gold from its electronic applications and molybdenum from its steel alloys, mainly due to the low amounts per product and the complicated material compositions, in which they are often embedded. For these cases, an increasing market price will have relatively little effect on the application of these materials in products. But this circumstance does not affect the general theorem that a higher market price of a material leads to a more economical use of that material.

2.2. Substitutability

If it is easier to substitute one material by another in a certain application without losing services or incurring unpalatable extra costs, it will be more acceptable and easier to agree to ban that material from use in that application or to impose a resource levy on the material.

Table 2 summarizes the substitutability of the five materials and shows that antimony and boron can be substituted to a substantial extent with existing technology: antimony in flame retardants, in batteries, and as PET catalyst; boron in its use in glass wool. By contrast, substitution of gold, rhenium, and molybdenum in their technical applications is very limited, given current knowledge and technology.

The Oakdene, Hollins, Fraunhofer substitutability system is developed in the framework of a project for the European Commission and is based on experts' opinions. For a number of elements, amongst others for antimony, boron, gold, rhenium and molybdenum we have also

Table 2
Substitutability of antimony, boron, gold, rhenium, and molybdenum.

Material	Substitutability [a]
Antimony	0.9
Boron	0.4
Gold	0.1
Rhenium	0.1
Molybdenum	0.0

[a] 0.0 = non-substitutable; 0.3 = substitutable at high cost and/or loss of performance; 0.5 = substitutable at some cost with/or some loss of performance; 0.7 = substitutable at low cost; 1.0 = easily and completely substitutable. The substitutability score system is derived from Oakdene Hollins, Fraunhofer (2013).

carried out an own research. The substitutability figure represents roughly the proportional amount of the element, of which the application can be avoided by replacing it by another element or by changing the application as such. For more details on the substitutability of the five materials, it is referred to the Supplementary Information.

2.3. Recyclability

The ease of recycling a raw material affects the effectiveness of certain policy instruments such as the promotion/obligation of recycling-oriented design and subsidizing recycled raw material. Table 3 presents the present recycling rates and the ultimate recyclability of gold, antimony, boron, rhenium, and boron. For background, details, and references, see the Supplementary Information.

The conclusion is that gold is already recycled to a high extent, which can be only slightly increased. The recyclability of rhenium is also high, but the precise current end-of-life recycling rate is not known. The recycling rates of antimony and molybdenum are low but can be increased substantially. Antimony can also be substituted for a large part, but not molybdenum. The main option for achieving sustainable use of molybdenum is substantial increase of recycling. Boron's recyclability is limited, but it can relatively easily be substituted in some applications.

3. Eleven policy instruments analyzed and assessed

We now discuss and assess eleven policy instruments that might be used to promote substitution and recycling, thereby decreasing the extraction rate of geologically scarce mineral resources. They are presented in order of increasing comprehensiveness and legally binding status. The criterion used in the assessment is *the relative effectiveness* of the different policy instruments for each of the five materials investigated, i.e. the goal achievement expected from applying a certain instrument as compared to the goal achievement expected from applying other instruments for the same mineral resource.[4] The effectiveness assessments of eleven policy instruments for reducing the use of five scarce materials are based upon the expert judgement of the authors. It needs to be emphasized that they are relative: the deemed effectiveness of one instrument compared to the deemed effectiveness of other instruments. The assessments are ex ante and they are a best guess of the authors based on limited data on the effectiveness of the same instruments in other frameworks. The effectiveness of these instruments cannot yet be tested in reality. Further research will be needed to underpin the results of this ex-ante assessment. We conclude by summarizing the relative effectiveness of each of the instruments for achieving more sustainable use of antimony, boron, gold, molybdenum,

[4] Other criteria for assessing a policy instrument's suitability (see e.g. Konidari and Mavrakis, 2007; Mees et al., 2014):

Table 3
Present recycling rate and recyclability of five scarce materials.

	Present recycling rate	Reference	Ultimate recyclability	Reference
Gold	> 90%	Butterman and Amey (2005)	> 90%	Butterman and Amey (2005)
Antimony	25%	Carlin, 2006; Henckens et al., 2016c	70%	Henckens et al., 2016c
Boron	0%	Henckens et al., 2015	10%	Henckens et al., 2015
Rhenium	?		> 80%	Own estimate, see Supporting Information
Molybdenum	20%	Henckens et al., 2018	< 80%	Henckens et al., 2018

and rhenium.

3.1. Necessary first step: establishing an international competence center on mineral resources management

Global governance of the use of mineral resources requires thoughtful technical and scientific preparation at global scale. We believe that a prerequisite for a future global mineral resources governance system is to establish an International Competence Center on Mineral Resources Management, following the example of the Intergovernmental Panel on Climate Change (IPCC), which has raised global attention for climate change and awareness of the urgency of addressing this problem and has galvanized and coordinated thousands of scientists to address the problem. Another positive example of international coordination is the Ozone Secretariat, which has been established in the framework of Montreal Protocol on Substances That Deplete The Ozone Layer.

The main tasks of an International Competence Center on Mineral Resources Management would be (Bringezu et al., 2016):

- Keeping estimates of extractable global resources up-to-date
- Monitoring global resources use
- Establishing a database of extractable global resources estimates and global resources use
- Developing a Global Mineral Resources Management Program

The nucleus of the Competence Center could be the International Resources Panel on the Sustainable Use of Natural Resources, set up in 2005 on the initiative of the European Commission and UNEP (European European Commission, 2005). Without the application of other instruments described below, establishing such a Center alone will not have a big impact, but the Center is a prerequisite for prioritizing, elaborating, and creating the other policy instruments, and for making them effective.

3.2. No dedicated policies

Not having dedicated policies assumes that the price mechanism of the free market will react on time and automatically solve problems of geological scarcity of mineral resources, because as a resource becomes scarcer its price will rise, making substitution and recycling more attractive. This approach is advocated by resource optimists such as Barnett and Morse (1963); Simon (1980 and Simon (1981)), Maurice and Smithson (1984), and more recently by Lomborg (2001) and Diamandis and Kotler (2012).

As explained in section 2, the price mechanism will work well for precious resources such as gold and rhenium but not for lower-priced commodities such as antimony, molybdenum, and boron. It is uncertain whether the market prices of these three will rise at short notice in response to their geological scarcity. We conclude that this option is very effective for precious materials such as gold and rhenium, but cannot be relied on for antimony, boron, and molybdenum. Hence, the following assessment of the ten other policy instruments excludes gold and rhenium.

3.3. Guidelines, recommendations, and codes of conduct

Existing guidelines for multinational companies stimulating the economical use of natural resources include the *OECD Guidelines for multinational enterprises*, *The Sustainability Framework* of the International Finance Corporation (IFC) of the World Bank, and the *Business Charter for Sustainable Development Coalition for Environmentally Responsible Economies — The ten environmental principles* of the International Chamber of Commerce. Other relevant guidelines are guidelines 14040–14049 of the International Standardization Organization (ISO) on Life Cycle Assessment (LCA). LCA includes abiotic resource depletion. Developing and promoting guidelines, recommendations, and codes of conduct specifically for scarce raw materials could be one of the tasks of the International Competence Center on Mineral Resources Management. However, like Pattberg (2006), we consider this a relatively ineffective way of reducing the use of mineral resources. The main weakness of guidelines, recommendations, and codes of conduct is that they are voluntary, necessarily general, and often lack specific performance standards.

3.4. Eco-labeling

If an eco-label has continued government support and sufficient budget for a clear and consistent information campaign, it can influence consumer choice (Van Amstel et al., 2008). The International Competence Center on Mineral Resources Management could develop recommendations on the requirements for an eco-label on scarce mineral resources. None of the existing eco-label systems includes the impact on exhaustion of mineral resources, so an option could be to include scarcity of mineral resources within existing eco-labels or to create a new dedicated label indicating the amount of scarce mineral resources a product contains. Given the plethora of eco-labels, the former is preferable. WTO rules permit eco-labels related to conserving exhaustible natural resources, providing they do not discriminate between foreign and domestic products.

We assess eco-labeling as only moderately effective because it is facultative and its success depends on consumers' motivation and finances. The main factor determining the decision to buy is product price (Brécard et al., 2009; Teisl et al., 2002; Banerjee and Solomon, 2003).

3.5. Sustainable purchasing

Sustainable purchasing has a positive effect on the results of ISO 14001 environmental management implementation (Beamon, 1999; Chen, 2004). A condition for the effectiveness of sustainable purchasing of products by private business and government is the availability of clear information on the impact of products during their life cycle on the environment, climate change, and exhaustion of natural resources. Thus sustainable purchasing will be facilitated by eco-labels. Incorporating mineral resources scarcity into existing national eco-labels will make it easier for governments and business to use scarcity as a criterion in their purchase policy.

We assess that this instrument is only moderately effective because it is not obligatory.

3.6. Promoting recycling-oriented design

Recycling-oriented design increases the potential for product repair, the potential for reusing components containing scarce mineral resources, the recyclability of the scarce mineral resources contained in a product, and can help decrease the in-use dissipation of a scarce material (Ciacci et al., 2015). Unless made mandatory, recycling-oriented design will primarily remain dependent on the initiative of private producers. We found no scientific literature on the effectiveness of recycling-oriented design in general. However, we expect a similarity with the effectiveness of eco-labels. If consumers are informed about the recycling-oriented design of a product, some may be motivated to buy it even if it costs more (as in the case of Fair phone). However, as with eco-labels, we expect that product price will remain the main decisive factor for most consumers. To overcome the facultative character of recycling-oriented design, governments could require selected scarce materials only to be used in products from which they can be easily retrieved. The International Competence Center on Mineral Resources Management could advise on recycling-oriented design of specific products.

Recycling-oriented design is ineffective for boron because of its low recyclability (< 10%) but is effective for recovering antimony and molybdenum. Users and recyclers are largely unaware of the presence of antimony or molybdenum in products. If recycling oriented design of products containing antimony and molybdenum was mandatory, the recycling rate of these metals would greatly improve.

3.7. Subsidizing secondary materials

This would encourage the use of secondary (recycled) resources instead of primary (virgin) resources. Making the recycled materials cheaper than their virgin equivalents will encourage the market and the cheapest recycling technologies. Government subsidies for specific recycling technologies seem inadvisable because this might inhibit innovation of recycling technologies (Chen, 2005; Söderholm and Tilton, 2012). By subsidizing the use of secondary materials instead of primary resources, any recycling technology would be supported and not particular technologies.

Combining subsidies for recycled materials with scarce resource levies on the related primary mineral resource would put the financial burden on the users of primary scarce materials instead of on ordinary tax payers. Again, boron's low recyclability makes this strategy ineffective. It is effective for antimony and molybdenum because the market price of the primary material is mostly lower than the cost of the secondary (recycled) material. However, subsidizing a recycled material could discourage substitution if the secondary material is kept cheap artificially. Subsidizing recycled materials needs a customized (i.e., national) approach. In Europe, it should be organized at EU level to avoid waste streams flowing to countries with the highest subsidies.

3.8. Prohibiting and/or taxing disposal of scarce materials

The subsidizing of recycled secondary materials may be complemented by prohibiting disposal (via landfill or incinerators) of products containing scarce mineral resources or by imposing levies on their disposal. This will encourage recycling of the products concerned (Calcott and Walls, 2000; European European Commission, 2012). It would be effective for antimony and molybdenum, but not for boron because of its low recyclability.

3.9. Scarce resource taxation

Taxing scarce resources makes products containing the taxed materials more expensive and less competitive (Gerlagh and van der Zwaan, 2006; Goulder and Schein, 2013), causing demand for these products to decrease. Four schemes are possible (European Environment Agency, 2012): global resource taxation; taxation of extraction by resource countries; material input taxation at first use of the raw material; and taxation of consumption. Of these, taxation on consumption is the only scheme which looks feasible in the short- and midterm. Unlike the other three types of taxation, it can be organized and imposed nationally. The main challenge is to design a system that is not too complex yet reflects the use of scarce resources.

Countries have a limited scope regarding scarce resource taxation because their taxation policy cannot differ greatly from the related policy of neighboring countries. The obvious approach is coordination between neighboring countries regarding taxation of the sale and use of scarce mineral resources and products containing them, combined with border tax adjustments, if needed.

We assess that scarce resource taxation is effective for antimony, boron, and molybdenum.

3.10. Banning

A well-known example is the successful worldwide phasing-out of ozone-depleting substances in the Montreal *Protocol on Substances that Deplete the Ozone Layer* (1987). Polychlorinated Biphenyls (PCBs) were banned in 2001 by the Stockholm *Convention on Persistent Organic Pollutants*. Via REACH (the EU Directive on the *Registration, Evaluation, and Authorization of Chemicals*, 2006), the European Union has banned cadmium from certain applications. The EU *Restriction of Hazardous Substances* Directive (2009) limits the use of certain substances in electronical and electronic equipment. Similarly, geologically scarce mineral resources could be banned from use in certain applications. Priority should be given to applications in which scarce raw materials can easily be substituted by less scarce substances without loss of services and with negligible (or no) extra costs. A product ban should focus not on minor applications but on low-hanging fruits, i.e., most applications of antimony (e.g. in flame retardants, lead-acid batteries and as PET catalyst) and some applications of boron (e.g. the applications in glass wool and a number of detergents). Banning of applications does not offer an effective solution to reduce molybdenum use because of its low substitutability. The International Competence Center on Mineral Resources Management could advise on possibilities and prioritization in this respect.

3.11. Extraction quotas established jointly by resource countries

In theory, international quotas would very effectively reduce the global extraction rates of antimony, molybdenum, and boron to controllably sustainable rates without further government actions. A fast way of achieving this if a scarce mineral resource is extracted in only a few resource countries is for these countries to agree on extraction quotas. Table 4 shows that the majority of the world reserves of antimony, boron, and molybdenum are each concentrated in only four to six countries.

The advantages of limiting the extraction of certain scarce mineral

Table 4
Percentage of world reserves. Derived from data of USGS (2018b).

	Antimony	Boron	Molybdenum
China	31%	3%	49%
Russia	23%	4%	6%
Australia	9%		
Bolivia	20%		
Chile		3%	11%
United States	4%	4%	16%
Peru			13%
Turkey	7%	86%	
Total % of global Reserves	94%	97%	95%

resources to a sustainable rate via an agreement between resource countries rather than via a global agreement under UN auspices are:

- Resource countries keep sovereignty over the natural resources on their territory
- Arranging an agreement between a few countries with similar interests will probably be faster than doing so for many countries with diverse interests
- The transaction costs of an agreement between a few countries are much lower.

The most important disadvantages are:

- Free riders (non-participating countries) may frustrate the agreement
- Participating countries may fail to comply
- User countries will depend more on the policy of a few resource countries and may look for their own resources of these elements
- Poor user countries will find it more difficult to negotiate on a special position than in a UN framework
- Single-resource countries could be more susceptible to geopolitical pressure.

An agreement between resource countries seems possible only if it is in their interests (financially or otherwise) in the short and long terms; at the least, the agreement must not be disadvantageous. This means that the resource countries should be allowed by the other countries to establish proportionally higher tonnage prices for the reduced amount of extracted mineral resources in such a way that they do not lose revenue. A current example of resource countries coordinating resources policies is the Organization of Petroleum Exporting Countries (OPEC). It is estimated that 70–75% of the world's proven reserves are in OPEC countries (Lai, 2008). OPEC's goal is to stabilize oil prices by fixing the total oil production of member countries and allocating production among the member countries by a quota system. The allocation is the result of negotiations between the member countries.

Although OPEC plays a significant role, its effectiveness fluctuates because of conflicts between OPEC countries, differences in their interests and wealth, and the interference of non-OPEC countries such as Russia. The OPEC experience shows the difficulty of achieving long-lasting, harmonious agreements between resource countries, especially when countries have conflicting interests and different cultures. However, resource countries could usefully draw on OPEC's experiences when discussing the possibilities of limiting the extraction of geologically scarce mineral resources with a view to using these more sustainably and conserving them for future generations.

An agreement between resource countries on limiting the extraction and export of scarce raw materials would not contravene the General Agreement on Tariffs and Trade (GATT). Notwithstanding the general rule prohibiting export restrictions, in Article XX(g), GATT allows export restrictions if these are related *"to the conservation of exhaustible natural resources"* and "*if such measures are made effective in conjunction with restrictions on domestic production or consumption*". Resource countries may themselves agree to reduce extraction but to preclude potential free riders and non-compliant resource countries, it would be preferable to secure the approbation of the world community and the protection of the agreement by the United Nations and the World Trade Organization. These organizations could conditionally agree to ban free riders and non-compliant resource countries from the international market. The conditions could, for example, concern an international agreement on a phasing-down scheme and trends in the resource price. If resource countries establish extraction quotas they will not be obliged to compensate developing countries for the increased costs of importing the scarce mineral in question.

3.12. Establishing extraction quotas under the auspices of the United Nations

The purpose of a global agreement is to make existing UN Policy on the sustainable use of natural resources operational. The approach is elaborated in more detail by Henckens et al., 2016a. An international arrangement under the auspices of the United Nations is complex because many different interests are involved (e.g. Dimitrov, 2013; Zelli et al. (2016); Abbott and Snidal, 2000 and Abbott and Snidal (2009); Biermann et al., 2009; Biermann, 2011; Widerberg, 2016). The principle of permanent sovereignty of nations over their natural resources will be particularly difficult to overcome in a global agreement because nations do not want to lose control over their national territory, even in the interests of addressing a *common concern of mankind*[5], which might be the case for the conservation of scarce mineral resources for future generations.

In the past, the United Nations has tried to regulate commodity markets through International Commodity Agreements such as the International Sugar Agreement (1954–1983), the International Cocoa Agreement (1972–1988), the International Coffee Agreement (1962–1989), the International Natural Rubber Agreement (1980–1999), and the International Tin Agreement (1954–1985). Since 1976 these Agreements have been embedded in UNCTAD's Integrated Program for Commodities. The main purpose of the agreements was price stabilization. All have failed. According to Gilbert (1996), the explanation for these failures is "*public intervention in commodity markets is not easily rationalized within a climate in which competitive markets are encouraged and state interventions are seen as requiring clear justification in terms of market failure*".

There are no strong global institutions which could enforce global regulation on sustainable use of scarce resources. Even if an agreement were formulated and ratified at the level of the United Nations, individual countries would need to implement the necessary measures.

An advantage of an international arrangement under the auspices of the UN is that fairness and equity for poor user countries can better be guaranteed in principle. The UN could establish a system of financial compensation of poor user countries, which would need to be financed by the main resources users: the industrialized countries.

The International Competence Center on Mineral Resources Management could be asked to advise on creating a draft international agreement on the sustainable use of scarce mineral resources.

3.13. Effectiveness of policy instruments summarized

Table 5 summarizes our preliminary conclusions regarding the relative effectiveness of the eleven different policy instruments for reducing the use of antimony, boron, gold, molybdenum, and rhenium resources.

4. Conclusions and discussion

In pursuit of suitable policy instruments for achieving a more sustainable use of scarce mineral resources to avoid future generations being confronted with sudden depletion of certain mineral resources and correspondingly sharply increasing prices we distinguished eleven policy instruments. We investigated their relative effectiveness for five

[5] The *common concern of humankind* principle is included in e.g. the preambles of the 1992 United Nations Framework Convention on Climate Change and of the 1992 Convention on Biological Diversity. According to several scholars (Brunnée, 2007; Schrijver, 2008; Perrez, 2000; International Law Association, 2014) this principle implies that permanent sovereignty should be exercised for the benefit of mankind, which consists of present and future generations. Thus far, depletion of scarce mineral resources has not specifically been identified as a *common concern of mankind.*

Table 5
Authors' ex ante assessment of the relative effectiveness of eleven policy instruments for reducing the use of five scarce raw materials. The scores are explained in the paragraphs.3.1–3.11.

Policy instrument	Effectiveness*			
	Antimony	Boron	Molybdenum	Gold and Rhenium
No dedicated policies	–	–	–	+ +
Guidelines, recommendations, codes of conduct	–	–	–	–
Eco-labeling	0	0	0	–
Sustainable purchasing	0	0	0	–
Promoting/prescribing recycling-oriented design	+	–	+	–
Subsidizing recycled scarce materials	+	–	+	–
Prohibiting or taxing disposal of products containing geologically scarce mineral resources;	+	–	+	–
Resource taxation	+	+	+	–
Banning the sale and use of certain application;	+ +	+ +	–	–
Establishment of extraction quotas by resource countries	+ +	+ +	+ +	–
Establishment of extraction quotas by the United Nations	+ +	+ +	+ +	–

*– ineffective, - slightly effective, 0 moderately effective, + effective, + + very effective.

scarce mineral resources: antimony, boron, gold, molybdenum, and rhenium. The first conclusion is that there is no single recipe for achieving more sustainable use of mineral resources. Which instruments are most effective depends on the specific characteristics of the mineral resource. Determinative variables are a material's market price, substitutability, and recyclability. The second conclusion is that the establishment of an International Competence Center on Mineral Resources Management is a necessary condition for an effective global approach for prioritizing and implementing the other policy instruments.

We also conclude that not all scarce mineral resources need dedicated policy instruments to achieve their prudent use. Such instruments are unnecessary for highly precious materials such as gold and rhenium. For less precious materials, such as antimony, boron, and molybdenum, the most effective approach would be an international agreement on the establishment of sustainable extraction quotas. This could be arranged by all (or the major) resource countries, or under the auspices of the United Nations.

Banning is very effective for applications which are easily substitutable: the use of antimony in flame retardants, lead-acid batteries, as a catalyst for PET production, as heat stabilizer, and in ceramics. These account for over 85% of antimony's use. Boron could be banned from its application in glass wool because glass wool can be substituted by rock wool. This concerns about 40% of boron's use.

Scarce resource taxation is effective for antimony, molybdenum, and boron.

Promoting or prescribing sustainable design, subsidizing recycled materials and prohibiting (or taxing) disposal are considered effective for antimony and molybdenum, but not for boron because boron is hardly recyclable from its applications. Eco-labeling and sustainable purchasing are only moderately effective for antimony, boron, and molybdenum, because they rely on consumer conscience. Guidelines, recommendations, and codes of conduct are not very effective for any of the five materials.

Credible global agreements require strong global implementing institutions and global enforcement and judicial bodies. Though UN agreements are legally binding, there is no independent body to enforce them. Nevertheless, empirical research has revealed that international regimes make a difference (Andresen, 2013; Breitmeier et al., 2006). Worldwide commitment to the sustainable use of scarce mineral resources will be achieved faster if broad international acceptance of other measures for achieving such use already exists Falkner (2018). The policy options available for achieving sustainable use of scarce mineral resources are not mutually exclusive but complementary. However, an agreement on extraction quotas will make the other policy instruments redundant.

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Appendix A. Supplementary data

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References

Abbott, K.W., Snidal, D., 2000. Hard and soft law in International Governance. Int. Organ. 54 (3), 421–456 2000.
Abbott, K.W., Snidal, D., 2009. Strengthening international regulation through transnational new governance: overcoming the orchestration deficit. Vanderbilt J. Trans. Law 2009 (42), 501–578.
Ali, S.H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enriquez, M.A., Kinnaird, J., Littleboy, A., Meinert, L.D., Oberhänsli, R., Salem, J., Schodde, R., Schneider, G., Vidal, O., Yakovleva, N., 2017. Mineral supply for sustainable development requires resource governance. Nature, vol 543, 367–372 16 March 2017.
Andresen, S., 2013. In: Falkner, Robert (Ed.), International Regimes Effectiveness, The Handbook of Global Climate and Environment Policy, Chapter 18, 1st edition. 2013 John Wiley & Sons Ltd.
Banerjee, A., Solomon, B.D., 2003. Eco-labeling for energy efficiency and sustainability: a meta-evaluation of US programs. Energy Policy 31 (2003), 109–123.
Barnett, H., Morse, C., 1963. Scarcity and Growth, The economics of Natural Resource Availability. John Hopkins University Press for resources for the Future, Baltimore, MD.
Beamon, B., 1999. Designing the green supply chain. Logistics Information Management, 12,4,1999,332-342. MCB University Press.
Biermann, F., 2011. International Organizations and Global Environmental Governance: Toward Structural Reform, From Handbook of Global Environmental Politics, 2nd edition. .
Biermann, F., Davies, O., Van der Grijp, N., 2009. Environmental policy integration and the architecture of global environmental governance, International Environmental Agreements: politics. Law Econ August 2009, 1-25.
Binnemans, K., Jones, P.T., Van Acker, K., Blanpain, B., Mishra, B., Apelian, D., 2013. Rare earth economics: the balance problem. JOM 65 (7), 846–848 2013.
Brécard, D., Hlaimi, B., Lucas, S., Perraudeau, Y., Salladarrée, F., 2009. Determinants of Demand for Green Products: An Application to Eco-label Demand for Fish in Europe.
Breitmeier, H., Young, O.R., Zürn, M., 2006. Analyzing International Environmental Regimes, From Case Study to Database. MIT Press.
Bringezu, S., Potocnik, J., Schandl, H., Lu, Y., Ramaswami, A., Swilling, M., Suh, S., 2016. Multi-scale governance of sustainable natural resource use—challenges and opportunities for monitoring and institutional development at the national and global level. Sustainability 778 (8), 1–25. https://doi.org/10.3390/su8080778. 2016.

Brunnée, J., 2007. Common areas, common heritage and common concern. In: Bodansky, D., Brunnée, J., Hey, E. (Eds.), Oxford Handbook of International Environmental Law, 2007. Oxford University Press, Oxford.
Butterman, W.C., Amey, E.B., 2005. Mineral commodity profiles, gold, USGS Open-file report 02-303, 2005.
Calcott, P., Walls, M., 2000. Can downstream waste disposal policies encourage upstream "Design for Environment. Econ. Waste 90 (2), 233–237.
Calvo, G., Mudd, G., Alicia, Valero, Antonio, Valera, 2016. Decreasing ore grades in global metallic mining: a theoretical issue or global reality? Resource 5 (36). https://doi.org/10.3390/resources5040036. 2016.
Carlin, J.F., 2006. Antimony recycling in the United States in 2000. USGS 1196-Q, 2006.
Chen, C.-C., 2004. Incorporating green purchasing into the frame of ISO 14000. J. Clean. Prod. 13 (2005), 927–933.
Chen, C., 2005. An evaluation of optimal application of government subsidies on recycling of recyclable waste. Polish J. Environ. Stud 14,2,2005, 137-144.
Christmann, P., 2017. Towards a more equitable use of mineral resources. Nat. Resour. Res. https://doi.org/10.1007/s1053-017-9343-6. 2017.
Ciacci, L., Reck, B.K., Nassar, N.T., Graedel, T.E., 2015. Lost by design. Environ. Sci. Technol. 49, 9443–9451 2015.
Diamandis, P.H., Kotler, S., 2012. The Future is Better Than You Think. Free Press, New York.
Dimitrov, R.S., 2013. In: Falkner, Robert (Ed.), International Negotiations, Handbook of Global Climate and Environment Policy. John Wiley & Sons, Ltd 2013.
Erickson RL, 1973, Crustal occurrence of elements, mineral reserves and resources, in: USGS, Professional Paper820,1973, 21-25.
European Commission, 2005. Thematic strategy on the sustainable use of natural resources. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, COM(2005) 670 final.
European Commission, 2012. Use of Economic Instruments and Waste Management Performances, Final Report of BioIntelligence Service for the European Commission (DG ENV, Unit G.4, 10 April 2012.
European Environmental Agency, 2012. Resource Taxation and Resource Efficiency Along the Value Chain of Mineral Resources, ETC/SCP Working Paper 3/2012.
Falkner, R., 2013. The Nation-state, International Society and the Global Environment, Chapter 15 in the Handbook of Global Climate and Environment Policy, first edition. John Wiley & Sons Ltd. 2013.
Gerlagh, R., Van Der Zwaan, B., 2006. Options and Instruments for a Deep Cut in CO_2 Emissions: Carbon Dioxide Capture or Renewables, Taxes or Subsidies.
Gilbert, C.L., 1996. International Commodity Agreements: an obituary notice. World Dev. 1 (24), 1–19 1996.
Goulder, L.H., Schein, A., 2013. Carbon Taxes vs. Cap and Trade: a Critical Review, National Bureau of Economic Research, Working Paper 19338. August 2013. .
Graedel, T.E., Nassar, N.T., 2015. The criticality of metals: a perspective for geologists, from Jenkin. In: In: GRT, Lusty P.A.J., McDonald, I., Smith, M.P., Boyce, A.J., Wilkinson, J.J. (Eds.), Ore Deposits in an Evolving Earth 393. Geological Society, London, Special Publications, pp. 291–302.
Henckens, M.L.C.M., Driessen, P.P.J., Worrell, E., 2015. Towards a sustainable use of primary boron, Approach to a sustainable use of boron. Resour. Conserv. Recycl. 103 (2015), 9–18.
Henckens, M.L.C.M., Driessen, P.P.J., Ryngaert, C.M.J., Worrell, E., 2016a. The set-up of an international agreement on the conservation and sustainable use of geologically scarce mineral resources. Resour. Policy 49 (2016), 92–101.
Henckens, M.L.C.M., Van Ierland, E.C., Driessen, P.P.J., Worrell, E., 2016b. Mineral resources: geological scarcity, market price trends and future generations. Resour. Policy 49 (2016), 102–111.
Henckens, M.L.C.M., Driessen, P.P.J., Worrell, E., 2016c. How can we adapt to geological scarcity of antimony? Investigation of antimony's substitutability and other measures to achieve a sustainable use. Resour. Conserv. Recycl. 108 (2016), 54–62.
Henckens, M.L.C.M., Driessen, P.P.J., Worrell, E., 2018. Molybdenum resources: their depletion and safeguarding for future generations. Resour. Conserv. Recycl. 134 (2018), 61–69.
International Law Association, 2014. Legal principles relating to climate change. Washington Conference.
Jowitt, S.M., Mudd, G.M., 2014. Global gold: current resources, dominant deposit types and implications. Proc. Gold14@Kalgoorlie, Kalgoorlie, Western Australia. pp. 56–58.
Kesler, W.E., Wilkinson, B.H., 2008. Earth's copper resources estimated from tectonic diffusion of porphyry copper deposits. Geology March 2008, 255-258.
Konidari, P., Mavrakis, D., 2007. A multi-criteria evaluation method for climate change mitigation policy instruments. Energy Policy 35 (2007), 6235–6257.
Lai, S.C.S., 2008. Oil prices and the OPEC: Is There a Basis for International Action? Erasmus University Rotterdam June 2008.
Lomborg, B., 2001. The Skeptical Environmentalist, Cambridge University Press. United Kingdom.
Maurice, C., Smithson, C.W., 1984. The Doomsday Myth, 10,000 Years of Economic Crisis. Hoover Institution Press, Stanford University.
Mees, H.L.P., Van Soest, D., Driessen, P.P.J., Van Rijswick, M.H.F.M., Runhaar, H., 2014. A method for the deliberate selection of policy instrument mixes for climate change adaptation. Ecol.Soc. 19 2014, 2, 58.
Mohr, S.H., Mudd, G.M., Giurco, D., 2012. Lithium resources, production: critical assessment and global projections. Minerals 2 (2012), 65–84.
Mookherjee, A., Panigrahi, D., 1994. Reserve Base in relation to crustal abundance of metals – another look. J. Geochem. Explor. 51, 1–9.
Mudd, G.M., 2007. Global trends in gold mining: Towards quantifying environmental and resource sustainability? Resour. Policy 32 (2007), 42–56.
Mudd, G.M., Ward, J.D., 2008. Will sustainability constraints cause "peak minerals"? 3rd International Conference on Sustainability Engineering & Science: Blueprints for Sustainable Infrastructure.
Mudd, G.M., 2009. Canadian Metallurgical Society, Sudbury, Ontario, Canada, August 2009Historical Trends in Base Metal Mining: Back Casting to Understand the Sustainability of Mining, Proc. 48th Annual Conference of Metallurgists2009. Historical Trends in Base Metal Mining: Back Casting to Understand the Sustainability of Mining, Proc. 48th Annual Conference of Metallurgists.
Mudd, G.M., 2010. The environmental sustainability of mining in Australia: key mega-trends and looming constraints. Resour. Policy 35 (2010), 98–115.
Mudd, G.M., Weng, Z., Jowitt, S., Turnbull, I.D., Graedel, T.E., 2013. Quantifying the recoverable resources of by-product metals: the case of Cobalt. Ore Geol. Rev. 55, 87–98.
Mudd, G.M., Jowitt, S.M., 2014. A detailed assessment of global nickel resource trends and endowments. Econ. Geol. 109, 1813–1841.
Mudd, G.M., Jowitt, S.M., Werner, T.T., 2017a. The world's lead-zinc mineral resources: scarcity, data, issues and opportunities. Ore Geol. Rev. 80 (2017), 1160–1190.
Mudd, G.M., Jowitt, S.M., Werner, T.T., 2017b. The world's by-product and critical metal resources part I: uncertainties, current reporting practices, implications and grounds for optimism. Ore Geol. Rev. 86 (2017), 924–938.
Mudd, G.M., Jowitt, S.M., Werner, T.T., 2017c. The world's lead-zinc mineral resources: scarcity, data, issues and opportunities. Ore Geol. Rev. 80, 1160–1190.
Mudd, G.M., Jowitt, S.M., 2018a. Global Resource Assessments of primary metals: an optimistic reality check. Nat. Resour. Res. 27 (2), 229–240 2018.
Mudd, G.M., Jowitt, S.M., Werner, T.T., 2018b. Global platinum group element resources, reserves and mining – a critical assessment. Sci. Total Environ. 2018 (614-625), 622–623.
Nickless, E., 2017. Resourcing future generations: a contribution by the Earth Science Community. Nat. Resour. Res. https://doi.org/10.1007/s11053-017-9331-x.
Nishiyama, T., Adachi, T., 1995. Resource depletion calculated by the ratio of the reserve plus cumulative consumption to crustal abundance for gold. Nat. Resour. Res. 4 (3), 253–261.
Oakdene Hollins, Fraunhofer, 2013. Study on Critical Raw Materials at EU Level, a Report for DG Enterprise and Industry of the European Commission, 16 December.
Pattberg, P., 2006. The influence of global business regulation: beyond good corporate conduct. Bus. Soc. Rev. 111 (3), 241–268.
Perrez, F.X., 2000. Cooperative sovereignty: from independence to interdependence in the structure of international environmental law, 2000, kluwer law international. The Hague.
Ragnarsdottir, K.V., Sverdrup, H.U., Koca, D., 2012. Assessing Long Term Sustainability of Global Supply of Natural Resources and Materials, Sustainable Development – Energy, Engineering and Technologies – Manufacturing and Environment, February 2012, Chapter 5. pp. 83–116.
Rankin, W.J., 2011. Minerals, Metals and Sustainability. CSIRO 2011.
Schodde R, Exploration trends, finds and issues in Australia, Presentation to International Mining and Resources Conference 10th November 2015, Melbourne.
Schrijver, N., 2008. Sovereignty Over Natural Resources: Balancing Rights and Duties, 1997, Reprinted in 2008. Cambridge University Press, Cambridge (2008).
Singer, D.A., 2017. Future copper resources. Ore Geol. Rev. 86 (2017), 271–279.
Simon, J.L., 1980. Resources, population, environment: an oversupply of false bad news. Science 208, 1431–1438.
Simon, J.L., 1981. The Ultimate Resource. Princeton University Press, Princeton, NJ.
Skinner, B.J., 1976. A second iron age ahead? Am. Sci. 64 (1976), 158–169.
Söderholm, P., Tilton, J.E., 2012. Material efficiency, an economic perspective. Resour. Conserv. Recycl. 61 (2012), 75–82.
Sverdrup, H.U., Ragnarsdottir, K.V., Koca, D., 2014a. On modelling the global copper mining rates, market supply, copper price and the end of copper reserves. Resour. Conserv. Recycl. 87 (2014), 158–174.
Sverdrup, H., Koca, D., Ragnarsdottir, K.V., 2014b. Investigating the sustainability of the global silver supply, reserves, stocks in society and market price using different approaches. Resour. Conserv. Recycl. 83 (2014), 121–140.
Sverdrup, H.U., Ragnarsdottir, K.V., Koca, D., 2015. Aluminium for the future: modelling the global production, market supply, demand, price and long term development of the global reserves. Resour. Conserv. Recycl. 103 (2015), 139–154.
Sverdrup, H.U., 2016a. Modelling global extraction, supply, price and depletion of the extractable geological resources with the lithium model. Resour. Conserv. Recycl. 114 (2016), 112–129.
Sverdrup, H.U., Ragnarsdottir, K.V., 2016b. A system dynamics model for platinum group metal supply, market price, depletion of extractable amounts, ore grade, recycling and stocks in use. Resour. Conserv. Recycl. 114 (2016), 130–152.
Sverdrup, H.U., Ragnarsdottir, K.V., Koca, D., 2017. An assessment of metal supply sustainability as an input to policy: security of supply extraction rates, stocks-in-use, recycling, and risk of scarcity. J. Clean. Prod. 140 (2017), 359–372.
Teisl, M.F., Roe, B., Hicks, R.L., 2002. Can eco-labels tune a market? Evidence from Dolphin-safe labeling. J. Environ. Econ. Manage. 43, 339–359.
Tilton, J.E., Crowson, P.C.F., DeYoung Jr, J.H., Eggert, R.G., Ericsson, M., Guzmán, J.I., Hunphreys, D., Lagos, G., Maxwell, P., Radetzki, M., Singer, D.A., Wellmer, F.W., 2018. Public policy and future mineral supplies. Resour. Policy(2018). https://doi.org/10.1016/j.resourpol.2018.01.006.
UNEP International Panel on Sustainable Resource Management, 2011. Estimating long-run geological stocks of metals, Working Group on Geological Stocks of metals, Working paper. April 2011. .
United Nations, United, 2015. Declaration of The High Level Political Forum on Sustainable Development, Sustainable Development Goal no 12.2, New York. pp. 25–27 September 2015.
USGS, 2017a. Historical Statistics for Mineral and Material Commodities in the United

States. 17-11-2017. https://minerals.usgs.gov/minerals/pubs/historical-statistics.
USGS, 2018a. Mineral commodity summaries, 2018, appendix C. Reserv. Resour.
USGS, 2018b. Mineral commodity summaries, January 2018, Antimony, boron, Molybdenum.
Alicia, Valero, Antonio, Valero, 2010. Physical geonomics: Combining the exergy and Hubbert peak analysis for predicting mineral resources depletion. Resour. Conserv. Recycl. 54 (2010), 1074–1083.
Van Amstel, M., Driessen, P., Glasbergen, P., 2008. Eco-labeling and information asymmetry: a comparison of five eco-labels in the Netherlands. J. Clean. Prod. 16 (2008), 263–276.
Weng, Z., Jowitt, S.M., Mudd, G.M., Hague, N., 2015. A detailed assessment of global rare earth resources: opportunities and challenges. Econ. Geol. 110 (2015), 1925–1952.
Widerberg, O., 2016. In: Pattberg, P., Zelli, F. (Eds.), Mapping Institutional Complexity in the Anthropocene, Environmental Politics and Governance in the Anthropocene, Chapter 6. Routledge, London and New York 2016.
Zelli, F., Pattberg, P., 2016. In: Pattberg, P., Zelli, F. (Eds.), Complexity, Responsibility and Urgency in the Anthropocene, Chapter 14 in Environmental Politics and Governance in the Anthropocene. Routledge, London and New York 2016.