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Molybdenum resources: Their depletion and safeguarding for future generations☆

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ABSTRACT

Comparison of the current extraction rate of molybdenum with the globally extractable resources of molybdenum shows that exhaustion of molybdenum within fifty to hundred years will be a reality. Unless measures are taken to reduce the use of primary molybdenum resources, the transition to a fossil-free energy world could be jeopardized. This study argues that the global use of primary molybdenum resources needs to be substantially reduced at short notice, if humanity wishes to take the interests of future generations into account. We investigated how this goal can be achieved. The study shows that the focus should be on increasing molybdenum recycling, because there is little or no substitution potential for molybdenum in its major applications. It will be necessary to increase the recycling rate of molybdenum from end-of-life products from the current rate of 20% to more than 80%. This ambitious goal can only be achieved by introducing a dedicated molybdenum waste collection, separation, and recycling system. It is highly uncertain that the free market price mechanism will work in time and sufficiently to preserve molybdenum resources for future generations.

1. Introduction

The global use of mineral resources has been increasing exponentially for a long time. Growth rates vary, but statistical data of the United States Geological Survey (USGS) show annual averages of about 3% over more than a century. The question is whether the Earth will be able to keep sustaining such growth in the future. In this respect, there have been repeated expressions of concern about the future availability of resources (among others Meadows et al., 1972, 1992; Rankin, 2011; UNEP, 2011a; Erickson, 1973; Nickless, 2018; Ragnarsdottir et al., 2012; Sverdrup et al., 2015).

In this paper we will focus on the possible depletion of molybdenum, because molybdenum is an important element for the infrastructure of modern society. More than 80% of molybdenum is applied in high quality steels to improve a range of characteristics, such as hardenability and ability to withstand high temperatures, seawater, and corrosive chemicals. Molybdenum is an essential metal in the framework of the transition to fossil-free power generation envisioned in the 2015 Paris climate agreement. According to Kleijn et al. (2011), a global non-fossil-fuel energy generation scenario would itself require almost as much as molybdenum as the current amount mined per annum.[1] Thus, ensuring the continuing availability of molybdenum is very important for society and even more for future generations.

Molybdenum use is rising very quickly. In 1950, global molybdenum production was 14,500 metric tons (USGS, 2017c). By 2015 this had increased to 235,000 metric tons. This is equivalent to sixteen-fold growth in a period of 65 years, or an annual growth rate of 4.4% (see Fig. 1).

This high growth rate will probably not continue forever. Research by Halada et al. (2008) clearly shows that after a certain GDP per capita threshold has been exceeded, growth of metal use starts to decouple from GDP growth. This decoupling starts at a per capita GDP of about USD 10,000 (1998).[2] Our explanation for this phenomenon is that once people attain a certain level of wealth, they start spending relatively more of their money on non-tangibles such as education, health, and culture, rather than on goods requiring metals, such as houses, cars, and

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[1] Wind power is the most iron and steel intensive of all power generation methods. Molybdenum is an important alloying agent used to strengthen the steel construction and reduce its weight. Molybdenum is also used to manufacture the high performance gear steels for wind turbines (International Molybdenum Association (IMOA), 2011). Molybdenum also plays an important role in thin film PV systems as one of the metals in the back electrodes of a thin film solar panel (International Molybdenum Association (IMOA), 2013).

[2] The development of metal use (MU) per capita per unit of GDP may differ from the development of the material footprint (MF) per capita per unit of GDP. In contrast to the clear decoupling of MU from GDP growth above a certain level of per capita, the relationship between GDP growth and MF is less visible (Schandl et al., 2017; Wiedmann et al., 2015).

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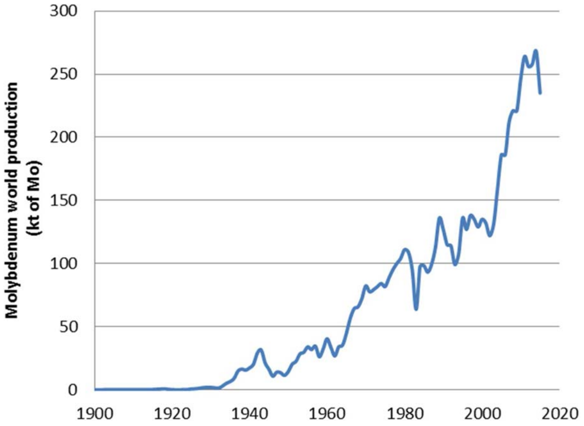

Fig. 1. World molybdenum production between 1900 and 2015 (kt/year). Derived from USGS (2017c).

washing machines. Let us suppose a realistic Business as Usual scenario, in which the average annual growth rate of molybdenum of 4.4% during the last 65 years (between 1950 and 2015) continues for another 35 years (until 2050), then decreases to 2% between 2050 and 2100 before finally flattening to 0% in 2100. It can be calculated that in that scenario, from 2100 onwards the annual molybdenum production rate will be in the order of 3 Mt per year, which is about twelve times higher than annual production in 2015. In that scenario, the amount of molybdenum produced in the 85 years between 2015 and 2100 will be about 15 times more than the total amount of molybdenum extracted in human history until 2015!

The intriguing question is whether such high molybdenum production figures will be sustainable and whether or not future generations will be confronted with a serious problem with respect to the availability of economically extractable molybdenum resources.

This paper aims at answering two questions. The first is whether molybdenum resources will be sufficient to sustain continued growth of molybdenum production and use and, if so, for how long. The second is which measures will be necessary and effective to achieve a sustainable situation with regard to molybdenum production and use. To address these issues, below we review, analyze, and assess the evidence from the scientific literature.

Our approach is as follows. In Section 2 we assess the literature data regarding extractable molybdenum resources. On the basis of the data collected, we will estimate when humanity could run out of molybdenum resources if no particular measures are taken. On the basis of a review of the literature on sustainability, in Section 3 we explore what could be a workable definition of the sustainable extraction rate of a mineral resource in general and of molybdenum in particular. Departing from this definition we will calculate the necessary reduction of the molybdenum extraction rate. In Section 4 we estimate the current molybdenum flows at a global scale. We do this to enable a systematic analysis of the effects of different measures for reducing the use of molybdenum resources.

In Section 5 we review the literature to ascertain the technical feasibility of reducing the use of primary molybdenum to a sustainable level without losing the services currently provided by molybdenum to society. First, we investigate the adequacy of the free market price mechanism to achieve a timely and sufficient reduction in the use of molybdenum resources with a view to the interests of future generations. Then we investigate the substitutability of molybdenum by other elements or alternative types of services, the potential for increasing the recovery of molybdenum at production, the material efficiency potential of molybdenum, the dissipation reduction potential of molybdenum, and the recycling potential of molybdenum. At the end of Section 5 we present some molybdenum recycling scenarios for reducing the molybdenum extraction rate to a sustainable level. In Section 6 we present our conclusions.

New in this paper are (1) an underpinned estimate of the remaining lifetime of molybdenum resources if no measures are taken, (2) a suggested extraction rate of molybdenum that is arguably sustainable, (3) observations on the interaction between the price mechanism and the depletion of mineral resources and (4) a description of the measures necessary for achieving a sustainable balance between molybdenum resources and molybdenum use.

2. Extractable molybdenum resources

In this section we assess molybdenum resources in the Earth's crust on the basis of different data and approaches in the literature. We have added our own approach.

The identified resources of molybdenum in the world have been estimated to be 19.4 Mt (USGS, 2017a). According to the definition of USGS (2017a), "*identified resources are resources whose location grade, quality, and quantity are known or estimated from specific geologic evidence. Identified resources include economic, marginally economic, and subeconomic components*". However, as not every inch of the crust has been explored for the presence of molybdenum, it can be assumed that the extractable molybdenum resources are larger than those identified to date. Note that identified resources are more than reserves. According to USGS (2017a), "*reserves are that part of the reserve base which could be economically extracted or produced at the time of determination"* and "*the reserve base is that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth*".

Rankin (2011) argues plausibly that the extractable global amount of a metal is proportional to the crustal abundance of that metal: (a) the size of the largest known deposit of each metal is proportional to the average crustal abundance of the metal (Skinner, 1976), (b) the number of known deposits of over 1 Mt of a metal is proportional to the average crustal abundance of that metal (Skinner, 1976), and (c) the reserve base of a metal is proportional to its upper crustal abundance (UCA). Observing this apparent correlation between extractable resources and upper crustal abundance, a working group of the International Resource Panel of UNEP (2011a) concluded that 0.01% of the total amount of a metal in the top 1 km of continental Earth crust is a "*reasonable estimate for the upper limit for the Extractable Global Resources*" of that metal. The percentage of 0.01% is based on earlier work of Skinner (1976) and Erickson (1973). From Erickson (1973) and Rankin (2011), it can be inferred that the estimate of the extractable global resources of an element ranges between 0.01% and 0.001% of the total amount of that element in the continental crust. Using the above UNEP approach we can calculate the amount of extractable global resources (EGR) of an element according to the formula

$$\mathrm{EGR} = 40 \times \mathrm{UCA}$$

EGR is expressed in Mt and UCA in ppm. See the Supplementary Information. Given that molybdenum's upper crustal abundance is 1.5 ppm (McLennan, 2001) or 1.5 g/t, the total amount of extractable molybdenum in the upper 1 km of the continental crust according to the approach of UNEP (2011a) is 60 Mt. This includes historical production of molybdenum. Below, we compare this result with the results of three other approaches.

Rankin (2011, p. 303) compared the results of 19 assessments of the estimated total (discovered plus undiscovered) deposits of gold, silver, copper, lead, and zinc in the United States of America with the resources identified by the USGS in 2000. The ratios of the estimated total deposits to the amount of identified resources for these five minerals ranged between 5.6 (for zinc) and 2.5 (for copper), and were on average 3.9. Applying this average ratio of 3.9 between total estimated resources and identified resources to global molybdenum resources yields

Table 1
Estimates of the extractable global amount of molybdenum.

Source	Specification	Estimated amount of molybdenum resources (Mt)
USGS (2017a), identified resources	Identified resources	19.4
Based on UNEP (2011a)	"Not unreasonable upper limit" of extractable global molybdenum resources, based on 0.01% of the total amount of molybdenum in the upper 1 km of the Earth's crust	60
Calculation according to Rankin (2011, p. 303)	Identified plus undiscovered resources, based on an assessment of the ratio between identified and undiscovered resources for five metals in the USA	76
Sverdrup et al. (2015)	Ultimate recovery rate	46
Own calculation of maximum recoverable amount of molybdenum	Ultimately recoverable amount of molybdenum, based on the estimated recoverable amount of molybdenum in porphyry copper resources	180

an extractable global amount of molybdenum of 76 Mt (identified plus undiscovered). Our estimate is not based on the globally identified resources in 2000 (17.5 Mt) but on the most recent data (19.4 Mt), because we assume that the crust in the rest of the world has been less explored than the crust in the USA.

On the basis of an estimate of the so-called extractable amount ore quality grading, Sverdrup et al. (2015) estimate the ultimate recovery rate of molybdenum at 46 Mt. This amount includes historical production of molybdenum.

We have also followed another approach to estimate the total amount of extractable molybdenum in the Earth's crust, departing from the estimated copper reserves in copper porphyry ores. Currently, 55–60% of molybdenum is produced as a by-product of copper extraction from porphyry copper ores (Peiró et al., 2013; USGS, 2010). This approach results in an estimated total amount of molybdenum of 180 Mt. See the Supplementary Information.

Table 1 presents an overview of the different estimates of available molybdenum resources.

Although knowledge on molybdenum resources on the seafloor in manganese nodules and seafloor massive sulfides is still limited, these resources do not seem to offer a solution. Though not negligible, seafloor resources of molybdenum are not high enough to change the overall picture fundamentally (Glasby, 2000; Hein et al., 2013; Sharma, 2011; Hannington et al., 2011).

The conclusion is that the estimated amounts of ultimately extractable molybdenum vary between about 50 and 180 Mt.

Among the methods used when discussing the finitude of a resource are the reserve to production ratio (RPR) method and the peak model method. The RPR is the amount of known reserves divided by the current annual production. The current RPR of molybdenum is about 65 years. The RPR is not an indicator of the number of years within which a resource will be exhausted, since new reserves continue to be found and the annual production rate changes; instead, it indicates the necessity of further exploration for a resource.

The peak model was developed by Hubbert (1956) for oil and gas. The theory is that the production of any finite resource over time, whether it is from an individual concentration, from a country, or from the planet, will follow a bell-shaped curve with a peak. The precise form of the peak will depend on past production and new discoveries. Early on, the production rate increases. Later, the curve declines again because of resource depletion. According to Sverdrup et al. (2013), molybdenum production will peak around 2050 and will be low again by 2150. According to Roper (2016), the peak year for molybdenum production will be around 2025.

Our approach is that we depart from the different estimates of the extractable amount of global molybdenum resources as presented in Table 1. The scenario we use to estimate the development of annual molybdenum production assumes rates mentioned in the introduction: 4.4% annual growth between 2015 and 2050, 2% annual growth between 2050 and 2100, and 0% annual growth from 2100 on. The purpose of this schematic approach is not to simulate the real development of molybdenum use, but to get an indication of the time period within which the threat of exhaustion of extractable molybdenum resources may become a reality. The actual development of molybdenum extraction will probably follow a bell-shaped path, as described above. Table 2 presents the results of our calculations of in how many years after 2015 molybdenum resources will become exhausted, assuming different estimates of available molybdenum resources.

Even the most optimistic estimate of extractable molybdenum resources results in a situation in which global molybdenum resources will be exhausted within about a century. If, instead of 4.4%, we assume a more optimistic scenario of 3% annual growth in extractable molybdenum between 2015 and 2015 and thereafter rates of 1.5% between 2050 and 2100, and 0% after 2100, then the number of years after 2015 until molybdenum exhaustion is only 70 years when using Sverdup's estimate of extractable reserves, 80 years for UNEP's estimate, 90 years for Rankin's estimate, and is 160 years for our estimate. So, even under the more optimistic scenario, the indisputable conclusion is that if humanity wants to conserve precious molybdenum resources for future generations, measures must be taken. The question that arises is when the use of molybdenum resources can be considered to be sustainable. The answer determines the extent to which the current extraction rate of molybdenum needs to be reduced.

3. Sustainable extraction rate of molybdenum resources

According the Declaration of the United Nations Conference on the Human Environment in Stockholm (1972) "*The non-renewable resources of the earth must be employed in such a way as to guard against the danger of their future exhaustion and to ensure that benefits from such employment are shared by all mankind*". This principle is repeated in the World Charter for Nature (1982), the Earth Charter (UNESCO, 2000) and the Report on the Implementation of Agenda 21 on Sustainable Development Goals. Sustainable Development Goal no 12 is: "*By 2030 achieve the sustainable management and efficient use of natural resources*".

How can the principle of sustainable development be made operational for molybdenum? An influential definition of sustainability was formulated in 1987 by the so-called Brundtland Commission: *"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). By 2007 there were already some 300 different elaborations of the concept of sustainable development (Johnston et al., 2007). Yet there is no definition that makes the sustainable extraction rate of a mineral resource operational, in the sense that such definition leads directly to a maximum global amount of molybdenum that may be extracted from the Earth's crust per unit of time.

Three factors determine the sustainability of the extraction rate of a mineral resource: the amount of extractable global resources, the period of time that extraction can be continued, and the extent to which the extraction rate takes account of inter-generational and intra-generational responsibility (Henckens et al., 2014). In theory, a sustainable extraction rate must be sustainable forever. However, we should realize that this is not possible, since the resources in the Earth's crust are not

Table 2
Molybdenum exhaustion for various scenarios.

Different estimates of the extractable global molybdenum resources (Mt) including historic extraction. See Table 1	46 (Sverdrup et al., 2015)	60 (UNEP, 2011a)	76 (Rankin, 2011)	180 (own estimate)
Historic (pre-2015) molybdenum extraction in Mt (USGS, 2017b), excluding extraction before 1900	7.4	7.4	7.4	7.4
Molybdenum extraction in 2015 (USGS, 2017b) (Mt)	0.235	0.235	0.235	0.235
Assumed development of molybdenum extraction	4.4% between 2015 and 2050, 2.0% between 2050 and 2100	4.4% between 2015 and 2050, 2.0% between 2050 and 2100	4.4% between 2015 and 2050, 2.0% between 2050 and 2100	4.4% between 2015 and 2050, 2.0% between 2050 and 2100, 0% after 2100
Molybdenum extraction between 2015 and 2050 (Mt)	20	20	20	20
Molybdenum extraction between 2050 and 2100 (Mt)	90	90	90	90
Remaining number of years after 2015 until molybdenum exhaustion, rounded	50	60	70	100

infinite. Even the smallest extraction rate will ultimately deplete molybdenum resources. That means that the sustainability period in a definition of the sustainable extraction rate of a resource must be a very long time, though not unreasonably long. The ideal situation is one in which the resource, once extracted, is reused maximally. However, some dissipation of the resource into the environment (finally to the ocean) is unavoidable. We propose a period of one thousand years as an acceptable horizon for the depletion of a resource. This is, of course, an arbitrary period. But in a definition of sustainable extraction rate, we consider a period of one hundred years as too short, because this would entail accepting that mineral resources are exhausted within a hundred years, when our grandchildren are still alive.

It is impossible to know or even to estimate how the world population will develop in the next one thousand years. In the short term it will increase to about 9 billion people by about 2040 and gradually increase further to about 11 billion by the year 2100, according to the medium population growth scenario of the United Nations (2015). For our definition of sustainable extraction rate we assume a world population of 9 billion. If the population develops differently, the definition can be adapted. It would be neither defendable nor acceptable for a definition of the sustainable extraction rate of a mineral resource to be based on the existing unequal distribution of material resources per capita over the world's countries. Our definition of a sustainable situation therefore assumes that resources per capita are distributed equally over the countries in the world. Our resulting definition of sustainable extraction rate of mineral resources is therefore: *The extraction rate of a mineral resource is sustainable if a world population of nine billion can be provided with that material for a period of at least one thousand years, assuming that the average per capita consumption of the mineral resource is equally divided over the world's countries* (Henckens et al., 2014).

The global extraction of primary molybdenum in 2015 was 34 g per capita (235,000 metric tons divided by 7 billion people). This is the average per world citizen. The annual molybdenum consumption in industrialized countries is about 150 g per capita (Halada et al., 2008). Using our definition of sustainable extraction, we calculated the reduction in the molybdenum extraction rate needed to for the rate to be considered to be sustainable. We did so for the four estimates of the available extractable molybdenum resources (see Table 3).

The conclusion is that regardless of the estimate of the extractable global molybdenum resources, the use of molybdenum resources needs to be reduced substantially, especially in the industrialized countries. The longer a reduction in extraction rate is postponed, the greater the reduction in the extraction rate will have to be to achieve a sustainable situation.

If we were to allow the depletion time in the sustainability definition to be 200 years instead of 1000 years, the necessary reduction in the use of molybdenum resources in industrialized countries vis-à-vis 2015 would still be 77% (instead of 95%), assuming extractable global resources of 60 Mt, unless we accept the existing unequal distribution of molybdenum resources over the countries in the world. The necessary reduction of molybdenum use in industrialized countries stays relatively high, even if the definition of the sustainable extraction rate is weakened, or if the estimates of the globally extractable amount of molybdenum rise to a substantially more optimistic level than the estimates in this paper.

4. Current molybdenum flows

The purpose of this sub-section is to quantify the anthropogenic flows of molybdenum. This will enable systematic exploration of how the various flows can be minimized (i.e. production, dissipation through use, down-cycling, waste disposal), or maximized (recovery at production, recycling).

The available scientific literature on anthropogenic molybdenum flows is scanty, so we have made estimates on the basis of data on

Table 3
Necessary reduction in molybdenum extraction under various assumptions about the extractable global resources of molybdenum, assuming a world population of 7 billion people in 2015.

Assumptions re extractable global resources of molybdenum. See Table 1 (Mt)	Sustainable per capita extraction based on 9 billion people in the future g/cap/year	Estimate of the current use of molybdenum resources in industrialized countries (2015) g/cap/year	Current use of primary molybdenum worldwide in 2015 (g/cap/year)	Necessary reduction of the use of molybdenum resources in industrialized countries, reference year 2015	Necessary reduction in the use of molybdenum resources at global level, reference year 2015
46	5	150	34	97%	85%
60	7	150	34	95%	79%
76	8	150	34	95%	76%
180	20	150	34	87%	41%

comparable other mineral resources. This approach provides a first indication which should be refined by future analyses.

4.1. Molybdenum loss at production

55–60% of molybdenum is a by-product or co-product of porphyry copper ore extraction. Porphyry copper ore accounts for 60% of world copper production (USGS, 2014a). In 2010, global copper production was about 16 Mt (USGS, 2012). Hence, the potential amount of molybdenum as a by-product or co-product of copper porphyry ore is about 290 kt in 2010, assuming a molybdenum content of 0.03% in porphyry copper ore (Habashi, 1997; cited by Ayres and Peiró, 2013). However, actual molybdenum production as by-product of copper was 133 kt in 2010, i.e., a recovery rate of 45% of the potential output, which is close to the recovery rate mentioned by Ayres and Peiró (2013). The amount of 133 kt molybdenum corresponds to 55–60% of total molybdenum production, including molybdenum from primary molybdenum mines. Using data on a number of other metals (Table 4) we assume a molybdenum recovery rate from primary molybdenum ore of about 80%. This leads to the conclusion that the overall recovery rate of molybdenum at production must currently be around 60%, which suggests there is room for improvement.

4.2. Molybdenum dissipation through usage

Molybdenum's applications worldwide are presented in Table 5.

Dissipation of molybdenum mainly occurs through its use in chemicals. The main applications of molybdenum in chemicals are in sulfurization catalysts, pigments, corrosion inhibitors, smoke suppressants, lubricants, and as a micronutrient in fertilizer (International Molybdenum Association (IMOA), 2015). According to Nakajima et al. (2007), in 2004 in Japan, 36% of molybdenum in chemicals was used as catalyst and was recycled. The other types of molybdenum-containing chemicals (e.g., pigments, corrosion inhibitors, smoke suppressants, lubricants, and fertilizer) are largely used in a dissipative way. Thus, based on the Japanese situation, dissipation of molybdenum from chemicals can be estimated at 64% of 12%, i.e. about 8% of the total molybdenum use. The additional dissipation of molybdenum from other applications will be relatively small, because of the type of application in metals and metal alloys. The wear of railroads can be mentioned, but the volume involved is small. Therefore, we assume that an approximate amount of about 10% of current molybdenum end-use is unavoidably dissipated and is not available for recycling.

Table 5
Molybdenum's applications in 2012 (International Molybdenum Association (IMOA), 2015).

Application	
Molybdenum grade alloy steels & irons	59%
Stainless steels	22%
Molybdenum metal	5%
Super alloys	3%
Chemicals	12%
Total	100%

4.3. Accumulation of molybdenum in anthropogenic stocks

We found no figures specifically on the accumulation of anthropogenic stocks of molybdenum. According to Chen and Graedel (2012), prior to 2012, no global-level cycle of molybdenum had been derived. According to Blossom (2002), the lifetime of molybdenum-containing products is between 10 and 60 years, but with an average of 20 years. This means that anthropogenic stocks of molybdenum are currently about 3.7 Mt. Similar to other metals, molybdenum's accumulation in a country's anthropogenic stocks differs, depending on the pace of that country's industrialization. Although further accumulation of molybdenum in the anthropogenic stocks of industrialized countries has slowed down in recent decades, it may increase again as a result of molybdenum being used in a fossil-free energy supply scenario (in wind turbines and solar cells). In industrializing countries, anthropogenic stocks of molybdenum are just beginning to accumulate and are doing so relatively rapidly. Data on the build-up of anthropogenic stocks of seven other metals are presented in Table 6.

A large proportion of molybdenum is used in high quality steel. This

Table 4
Metal content in ore, tailings, and slag at the production of seven metals.

Metal	Year	Metal content in tailings (kt)	Metal content in slag (kt)	Total metal content in tailings + slag (kt)	Total metal content in ore (kt)	Remaining in tailings + slag (% of total ore)	Source
Cu	1994	1300	–	1300	10,710	12%	Graedel et al., 2004
Zn	1994	1030	330	1360	7800	17%	Graedel et al. (2005)
Pb	2000	530	230	760	3500	22%	Mao et al. (2008)
Ag	1997	4	0.4	4.4	20.2	22%	Johnson et al. (2005)
Ni	2000	167	74	241	1,338	18%	Reck et al. (2008)
Fe	2000	92,000	28,000	120,000	694,000	17%	Wang et al. (2007)
Cr	2000	740	640	1380	5140	26%	Johnson et al. (2006)

Table 6
Flows to the anthropogenic stocks of 7 metals.

Metal	Year	To anthropogenic stocks in% of the quantity entering the use phase	Source
Chromium	2000	78%	Johnson et al. (2006)
Iron	2000	64%	Wang et al. (2007)
Nickel	2000	59%	Reck et al. (2008)
Silver	1997	48%	Johnson et al. (2005)
Lead	2000	11%	Mao et al. (2008)
Copper	1994	67%	Graedel et al. (2004)
Zinc	2010	35%	Meylan and Reck (2017)

is also the case for chromium and iron. We have therefor assumed that the molybdenum flow to anthropogenic stocks is the average of the equivalent flows of iron and chromium, i.e., around 70%. This means that the annual amount of molybdenum in end-of-life products is currently about 30% of the annual amount of molybdenum in new products entering the usage phase. Continuing growth of developing country economies will cause the further accumulation of molybdenum in anthropogenic stocks to decline gradually.

4.4. Current molybdenum recycling from molybdenum-containing products

About 88% of molybdenum is used in various alloys or as molybdenum metal (see Table 5). According to Blossom (2002), in 1998, old scrap molybdenum recycling efficiency (molybdenum recycled from old scrap divided by total molybdenum in old scrap produced) in the USA was 30%. This figure for old scrap molybdenum recycling efficiency is also used by UNEP (2011b). Based on a comparison between global end-of-life recycling rates with end-of-life recycling rates in the USA we estimate that the global end-of-life recycling rate of molybdenum is 20% (see the Supplementary Information). The main reason the amount of secondary molybdenum is so low is that old scrap containing molybdenum is normally purchased and recycled not for the sake of molybdenum, but for other metals, mostly iron. Steel scrap is processed in electric arc furnaces. Molybdenum and other elements such as nickel, cobalt, tungsten, and copper remain unintentionally in the molten steel (Nakajima et al., 2011). In this way, a substantial part of the molybdenum is down-cycled and "lost" in diluted form in various lower quality types of steel. The recycling efficiency of molybdenum is not expected to increase significantly as long as cheaper alternatives are available in the form of relatively cheap primary molybdenum.

4.5. Present-day molybdenum flows, summarized

Fig. 2 presents a simplified global anthropogenic molybdenum cycle for 2015. A sustainable extraction rate of molybdenum requires global extraction to be reduced by between 41% and 85%, depending on the estimated quantity of available extractable resources. This raises the question of how extraction of molybdenum resources can be reduced by these amounts vis-à-vis the current extraction rate. The annual molybdenum extraction in Fig. 2 would have to decrease from 392 kt to somewhere between 60 and 240 kt. In the following sections we will discuss to what extent substitution, material efficiency, dissipation reduction, and improved recycling can contribute to reducing the use of molybdenum resources.

5. Sustainable molybdenum flows

In this section we evaluate the options for reducing the use of primary molybdenum resources to a sustainable level. Based on the results, we will propose a strategy for achieving sustainable flows.

5.1. Possible role of the price mechanism

Are reduction measures really necessary? Surely the price mechanism of the free market will bring about a timely and adequate reduction of the molybdenum extraction rate? A price increase induced by molybdenum's geological scarcity could automatically lead to better material efficiency and more recycling. However, despite price hikes in recent years, the real price of molybdenum has remained remarkably stable: see Fig. 3. The long-term price trend of molybdenum does not (yet) reflect molybdenum's geological scarcity. This is true not only for molybdenum, but also for mineral resources in general. When we investigated whether there is a correlation between the geological scarcity of a mineral resource and its long-term price trend (Henckens et al., 2016) we concluded that, thus far, the prices of geologically scarce mineral resources have not risen significantly faster than the prices of non-scarce mineral resources. The explanation might be that the anticipation time of the market is limited to a few years or a few decades at maximum. Mining companies stop exploring if their exploitable reserves are sufficient for 20–30 years. The maximum forward time for futures on the London Metal Exchange is 123 months.

Hence, it is not at all certain that the price mechanism on its own will timely and sufficiently reduce the production and use of molybdenum to a sustainable level. Eventually, when molybdenum is nearly exhausted, we expect that the molybdenum price will increase, but that may be too late to safeguard sufficient molybdenum resources

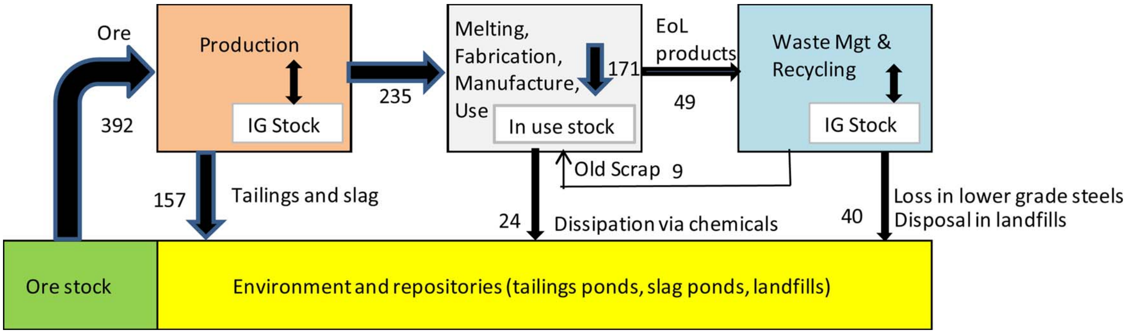

Fig. 2. Simplified global anthropogenic molybdenum cycle for 2015. Flows are in kt. End-of-life (EoL) recycling rate = 20% of amount contained in end-of-life products, tailings, and slags = 40% of ore; build-up in anthropogenic stock = 70% of molybdenum use; dissipation = 10% of molybdenum use. World mine production of molybdenum in 2015 was 235 kt. The arrow widths are a rough indication of flow magnitudes. IG stock = industrial, commercial, and governmental stocks.

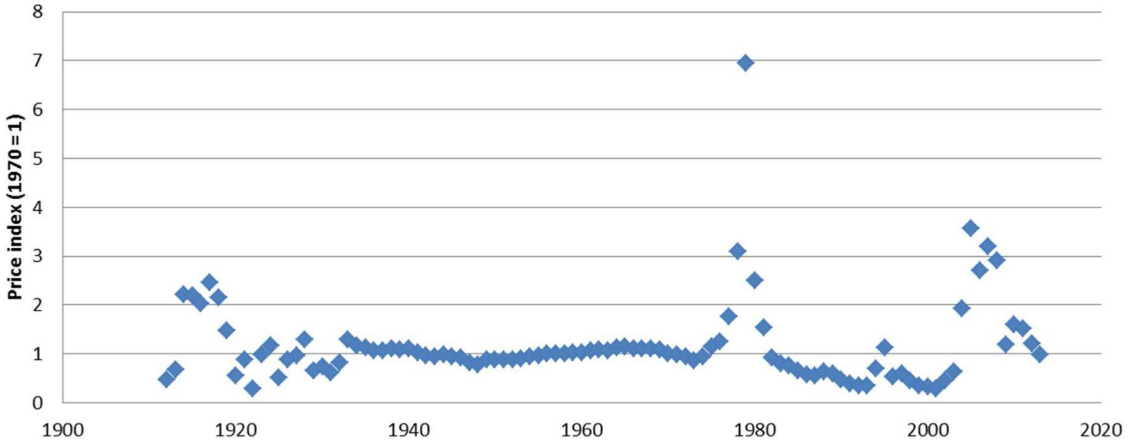

Fig. 3. Real price development of molybdenum expressed in 1998 USD, corrected for inflation and indexed on 1 in 1970 (USGS, 2014b).

for future generations.

5.2. Substitution of molybdenum

There is little scientific literature on the substitutability of molybdenum. According to the USGS (2017b) potential substitutes for molybdenum in some of its applications include:

- chromium, vanadium, niobium (columbium), and boron in alloy steels,
- tungsten in tool steels,
- graphite, tungsten, and tantalum for refractory materials in high-temperature electric furnaces,
- chrome-orange, cadmium-red, and organic-orange pigments for molybdenum orange.

However, most of the substitutes are geologically scarce themselves. In general, according to the USGS (2017b), there is little substitutability for molybdenum in its major application as an alloying element in steels and cast irons. Hollins and Fraunhofer,2013 have also concluded that in most applications molybdenum is not substitutable. Based on the above considerations we shall assume prudently that substitution of molybdenum cannot contribute to reducing primary molybdenum extraction.

5.3. Improving recovery during production

Based on data regarding other metals, we assume that it will be possible to increase molybdenum recovery as by-product of copper production from the current 45%–50% to 80% in the future. The molybdenum recovery from primary molybdenum mines is assumed to remain at 80% (see Table 4). For the combination of molybdenum as by-product of copper production plus molybdenum from dedicated molybdenum mines this will result in an *overall* increase of molybdenum recovery during production, from the current 60% to 80% in the future. However, the actual recovery rate will certainly depend on the molybdenum market price.

5.4. Improving molybdenum material efficiency

The material efficiency improvement potential indicates the potential reduction in material use required to provide the same service level as that of the original material use. For a specific material, an efficiency potential of 25% means that in order to provide the same services, only 75% of the original amount of that material would be needed. Based on an earlier study (Henckens et al., 2015) we assume a conservative (default) material efficiency potential of 10%, ignoring the impact of increased recycling of materials from end-of-life products and of an increase of molybdenum recovery when the raw material is being produced.

5.5. Reducing dissipation

The dissipative use of molybdenum is linked to its use in catalysts, pigments, corrosion inhibitors, smoke suppressants, lubricants, and fertilizer. The dissipation is partly direct (use as fertilizer), and partly indirect via landfills and incinerators. The only possibility to reduce this type of molybdenum dissipation is to diminish the use of molybdenum applications in chemicals. This might be possible for some of the applications, such as the more general use of molybdenum in pigments, as corrosion inhibitor, and as smoke suppressant. Nevertheless, we prudently assume that the assumed current dissipation of molybdenum (10%) cannot be reduced.

5.6. Necessary increase in molybdenum recycling for achieving sustainable molybdenum use

Table 3 in this paper shows that to safeguard sufficient molybdenum resources for future generations, global extraction of molybdenum needs to be reduced by 40–85% vis-à-vis 2015, depending on the estimate of available molybdenum resources. However, growth in molybdenum demand will not stop in the future, due to the increasing wealth of developing countries in combination with the transition to a fossil-free energy scenario. In Table 7 we investigate 20 scenarios in which molybdenum use varies between 2.5 and 4.5 times the current use and the reduction in molybdenum extraction is between 40% and 80% of the extraction in 2015. End-of-life recycling rates of metals higher than 90% are extremely difficult to achieve, especially from complex products. In the case of molybdenum, only rates below 80–85% are considered to be attainable in practice. The conclusion is that in a scenario with a molybdenum use three times higher than in 2015, the maximum reduction of the molybdenum extraction rate is about 40%. If we can limit future molybdenum use to 2.5 times the 2015 use, then the maximum reduction of the molybdenum extraction rate is about 50%. It can be demonstrated that it is impossible to achieve a more than 40% reduction of molybdenum extraction reduction when there is a more than three-fold increase in molybdenum use by society, unless dissipative use of molybdenum in chemicals is reduced and/or molybdenum is substituted in some of its applications. See the Supplementary Information. A more than three-fold increase in molybdenum use vis-à-vis 2015 is not sustainable, not even in the scenario with the highest estimate of available molybdenum resources.

Fig. 4 presents the scenario in which global molybdenum use per capita has increased to three times the 2015 global use of molybdenum

Table 7
Twenty scenarios for reducing molybdenum extraction vis-à-vis current (2015) use. The arrowed scenario is depicted in Fig. 4.

Molybdenum use scenarios	Molybdenum extraction in 2015 (kt)	Molybdenum production in 2015 (kt)	Extraction reduction scenarios %	Remaining extraction kt	Remaining molybdenum produced** (kt)	Assumed future molybdenum use (kt)	Molybdenum in future EoL products* (kt)	Necessary molybdenum recycling from EoL products (kt)	Minimum molybdenum recycling from EoL products %	Feasibility
Future molybdenum use is 4.5 times current molybdenum use	392	235	80%	78	63	1058	952	995	105%	impossible
	392	235	70%	118	94	1058	952	963	101%	impossible
	392	235	60%	157	126	1058	952	932	98%	impossible
	392	235	50%	196	157	1058	952	901	95%	extremely difficult
	392	235	40%	235	188	1058	952	869	91%	extremely difficult
Future molybdenum use is 3.5 times current molybdenum use	392	235	80%	78	63	823	740	760	103%	impossible
	392	235	70%	118	94	823	740	728	98%	extremely difficult
	392	235	60%	157	126	823	740	697	94%	extremely difficult
	392	235	50%	196	157	823	740	666	90%	extremely difficult
	392	235	40%	235	188	823	740	634	86%	difficult
Future molybdenum use is 3.0 times current molybdenum use	392	235	80%	78	63	705	635	642	101%	impossible
	392	235	70%	118	94	705	635	611	96%	extremely difficult
	392	235	60%	157	125	705	635	580	91%	extremely difficult
	392	235	50%	196	157	705	635	548	86%	difficult
→	392	235	40%	235	188	705	635	517	81%	difficult
Future molybdenum use is 2.5 times current molybdenum use	392	235	80%	78	63	588	529	525	99%	impossible
	392	235	70%	118	94	588	529	493	93%	extremely difficult
	392	235	60%	157	126	588	529	462	87%	extremely difficult
	392	235	50%	196	157	588	529	431	81%	difficult
	392	235	40%	235	188	588	529	399	75%	challenging

* This is 90 % of molybdenum use, due to 10 % dissipation

** This is 80 % of molybdenum extraction, due to 20 % loss to tailings and slag

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in combination with an end-of-life recycling rate of 81%. The assumed per capita molybdenum use is well below the current per capita molybdenum use in industrialized countries, which is five times the global amount per capita (Halada et al., 2008). In this scenario we have assumed that the amount of molybdenum in anthropogenic stocks has stabilized.

Assuming that the average product life time of molybdenum-containing products remains 20 years, the in-use stocks in Fig. 4 will be about 14 million metric tons in the depicted, stable, situation. Attaining the recycling requirement of 81% in this scenario is a tough challenge. To tackle it, it will be necessary to thoroughly investigate the recyclability of molybdenum at each step in the life cycle of a molybdenum-containing product: product design, collection of end-of-life products, dismantling of end-of-life products, scrap sorting, and processing. Additionally, a binding producers' responsibility system will be necessary to guarantee that the system works adequately. This is called material-centric or product-centric recycling (Van Schaik and Reuter, 2014).

6. Conclusions

Given the available molybdenum resources, molybdenum extraction is high. Unless adequate measures are taken, extractable molybdenum resources could be exhausted within fifty to hundred years. In order to secure the availability of sufficient extractable molybdenum for future generations, the extraction rate of molybdenum should be reduced considerably (in the range of 40–80% globally and by more than 90% in industrialized countries). It is highly uncertain whether the price mechanism of the free market will initiate such reduction in time and sufficiently.

There is little or no substitution potential for molybdenum in its major applications. Moreover, a substantial reduction of molybdenum dissipation through reduction of its application in chemicals also seems hardly possible. This means that the required reduction of molybdenum extraction has to take place through increased recycling of molybdenum and improved recovery at production.

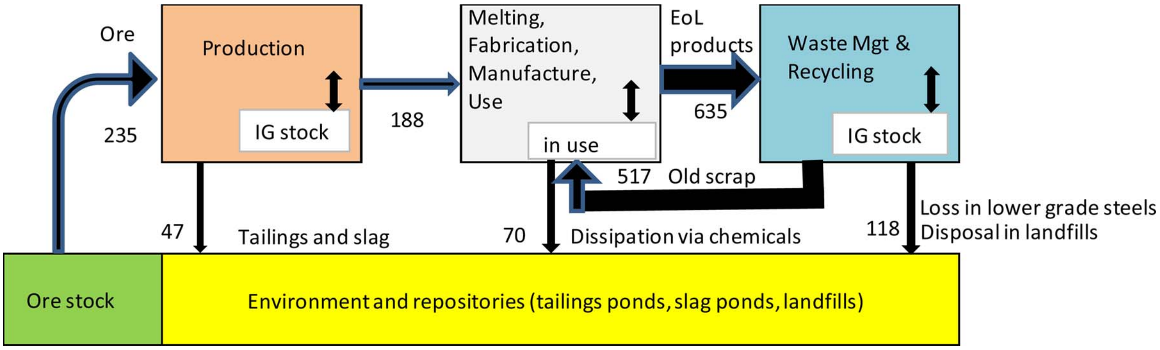

Fig. 4. Simplified sustainable global anthropogenic molybdenum cycle for obtaining 40% reduction of primary molybdenum extraction compared to the situation in 2015. The figures are in kt. Compared to Fig. 2, it has been assumed that molybdenum use has grown three-fold. Molybdenum recovery at production has increased from 60% at present to 80% in future. The new global end-of-life (EoL) recycling rate must be 81% instead of today's 20%. Substitution and dissipation reduction are both assumed to be 0%. Dissipation remains 10% of the usage, and substitution 0%. It has been assumed that there is no further accumulation of molybdenum in anthropogenic stocks. The arrow widths are a rough indication of flow magnitudes. IG stock = industrial, commercial, and government stocks.

Should we wish to enable molybdenum use in the future to grow to three times the current use, the maximum achievable reduction of molybdenum extraction is 40% compared to the extraction in 2015. This will require an end-of-life recycling rate of about 80%, which will not be easy to achieve and will require a product-centric recycling system combined with a producers' responsibility system. To reduce extraction rates by more than 40%, molybdenum will have to be substituted and dissipative use in chemicals limited.

To achieve the necessary reduction in molybdenum extraction, primary molybdenum mines would need to be closed and some of the molybdenum produced as a by-product of the copper mining would need to be stockpiled for use by future generations. It should be noted that copper is also a relatively scarce mineral resource, and its extraction might also need to be reduced to become sustainable. As long as molybdenum production continues to exceed sustainable production, it is important to stockpile molybdenum, to avoid the price for molybdenum being so low that it hampers sufficient molybdenum recycling.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.resconrec.2018.03.002.

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