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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 sixteenfold 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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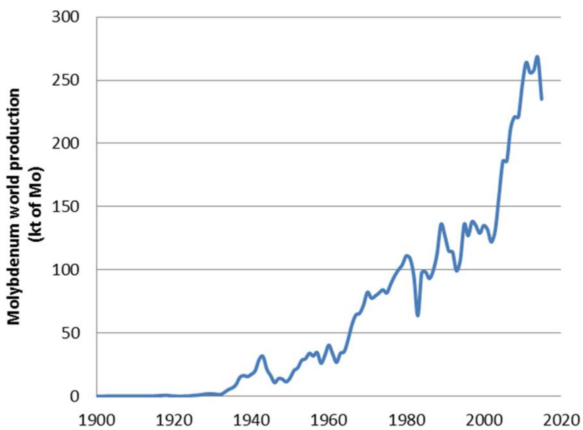

Fig. 1. World molybdenum production between 1900 and 2015 (kt/year). Derived from USGS (2017c).

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

$$EGR = 40 \times UCA$$

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