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An assessment of metal supply sustainability as an input to policy: security of supply extraction rates, stocks-in-use, recycling, and risk of scarcity

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ABSTRACT

The integrated model WORLD and Hubbert's model were used for assessment of future supply for different metals: iron, nickel, manganese, chromium, molybdenum, tantalum, niobium, rhenium, zirconium, tungsten, cobalt, copper, zinc, lead, aluminium and the technology metals derived from copper–zinc mining (tellurium, selenium, gallium, indium, antimony, bismuth, tin, germanium, selenium). The connections between their productions were mapped. The literature was reviewed for best estimates of total recoverable amounts, and best estimates were made, considering extraction costs and extractability. Peak years were determined for all the metals studied. Most metals seem to reach peak production during the next 4 decades, suggesting a risk for shortages in the near future. When supplies from mines dwindle, measures such as recycling from society's stock, substitutions to other materials than metals when this is possible, and stopped dissipative uses, will become important mitigation tools, calling for reorganization of resource policies world-wide. Present resource policies at all levels (regional, national, international) are to a large degree inadequate and need thorough review. The relevance of the Hubbert's model as an assessment tool was done. It is useful for all metals taken from independent ore deposits, whereas the method appears to be less suited for extraction of dependent metals unless the curve is derived from the Hubbert's model applied on the parent source. In such times, strategic thinking and strategic leadership based in systems thinking will be required.

1. Introduction

It is a fact beyond discussion that metal reserves represent finite resources, and that all mining diminish the reserves at the same pace as they are exploited (Ragnarsdottir, 2008, Ragnarsdottir et al., 2012, Heinberg, 2001, 2011; Bardi, 2013; Kerr, 2014). An integrated assessment of the security of long term supply and the adequacy of the Earth's metals reserves are therefore of strategic interest. Gordon et al. (2006), Rauch and Graedel (2007), Heinberg (2001, 2011), Bardi (2013) and Kerr (2014) along with the United Nations (UNEP, 2011a,b,c, 2013a,b,c) have presented these problems, pointing at a potential global material and metals scarcity situation in the future. We will estimate when there is a risk for scarcity for a selection of the most important metals for society, and examples from our assessment calculations will be shown. Judging from total tonnages, the two single most important metals for society appear to be iron and aluminium. In addition to iron, many other metals are included in steel which is so crucial for human infrastructures. Nickel, manganese, chromium and cobalt are included in different types of steel. Zinc and copper are other big metals in societal infrastructures, and of great economic importance. Copper, zinc aluminium and silver are important for electrical infrastructures, and silver, copper and gold for electronics. Indium, platinum and rhenium are important strategically for high technologies and as specialty catalysts.

2. Hypothesis, objectives and scope

Here we assess the adequacy of the metal supply and we document, for a number of metals, when maximum production

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rates can be expected and risks for scarcity situations may occur. This was done by using submodules of the global WORLD model (Sverdrup et al., 2014a,b) as well as the Hubbert's model (Hubbert, 1956, 1962, 1966, 1972). Only a few authors have to date published estimates of when peaks in metal production may occur in the future, and even fewer in peer-reviewed publications (Ragnarsdottir et al., 2011a,b, Sverdrup et al., 2012, 2013, 2014a,b, 2015). Our scope is to focus on some important aspects of the metal cycles and find quantifications for production rates over time, maximum production rates and estimates of peak events. We will address metal losses in relation to the degrees of recycling and waste recovery, extracted amounts mined to the present, and ultimately recoverable reserves. We also intend to evaluate the Hubbert's model per se, as well as the systems dynamics models used. Finally, we will discuss potential policy recommendations to government and business. We present our assessment of the necessary steps needed to create a long term sustainable situation with respect to societal metal supply. The issues of market availability, short-term dynamics and pricing in the past and future will be subject to separate studies and is outside the scope of this paper.

3. Methods and data

3.1. Theory and definitions

We used Hubbert's model which is designed to estimate the time horizon of raw materials and metal resources. Even if Hubbert's model is an empirical model, it does have a mechanistic explanation (Hubbert, 1972; Bardi and Yaxly, 2005). The equations used are identical to those found in Sverdrup et al. (2014a,b). The Hubbert's model was developed for oil production by M. K. Hubbert, a petroleum geologist at Shell Corporation in the early 1950's. It was applied with good success, and there is no scientific doubt that the model works well for oil, gas, and coal production. Hubbert tested the model for uranium and phosphate extraction, and this worked as well. What the model does not deal well with is substitution, recycling and reuse, and especially when recycling is activated by feedbacks from resource price and policy efforts. The Hubbert's model is fitted to the historical production data, using Ultimate Recovering Rates (URR). The Hubbert's model does have as a basic assumption that the extraction will go on at the maximum feasible speed, with no or little sub-capacity extraction. However, when we expect dynamic changes in the future, then simplified methods like burn-off rates and Hubbert's model are less suitable. Then fully integrated, process- and mechanism-oriented dynamic models are required. We have developed these kinds of large and complex sustainability assessment models earlier (Ragnarsdottir et al., 2011a, 2012; Sverdrup and Ragnarsdottir, 2011; Sverdrup et al., 2012, 2013, 2014a,b) in which exponential growth and market price mechanisms are mechanistically incorporated. One of the major advances were the development of a reality-based metal price model, allowing for price estimation from market fundamentals inside the models, without external forcing of functions or calibration. The outputs from the fully integrated systems dynamics models for silver, copper, aluminium, iron, steel, platinum group and bronze were used for the assessment. The comparison is used to evaluate the performance of the Hubbert's model and its relevance for metals.

3.2. Finding the input data

The data that are essential are observed data on past production rate versus time for the material studied and estimates of URR. The net supply to the system is depending on how much materials we can recycle. Fig. 1c shows an example of observations on required energy intensities for metal ore mining and milling for uranium, iron ore, mineral sands, silver–lead–zinc ores, and gold. We derive URR from the scientific literature and from corporate information. Mining costs are strongly connected to energy costs. Fig. 1b shows that metal recovery yields vary as a function of ore grade. Fig. 2a shows how URR for copper converge on a final size with time, and Fig. 1a how it depends on ore grade. Recovery rates from ore are important as it puts a limit on the URR estimates. URR do only depend on ore grade, but also on the fact that the lower the ore grade, the lower will the metal recovery rate be, and URR will converge towards a final limit. Fig. 2b shows how ore grades have gradually gone down for copper. The same pattern is seen for the platinum group metals, gold, silver, copper, zinc, lead, uranium, nickel and several other metals. Table 2 shows an overview of estimates of extractable amounts in 2012, earlier extracted and URR, with our best estimates of URR and traditional estimates reported by the United States Geological Survey (USGS, 2005, 2007, 2008, 2013), classified as illustrated in Table 1.

Fig. 3 shows a flowchart for metal extraction and how it is interdependent. This diagram is important for addressing when the Hubbert's model is a valid prediction tool or not. For primary materials extraction, the Hubbert's model can be shown to be a valid model. For dependent metals without their own independent orebody, the method is unsuitable.

For the dependent metals cadmium, bismuth, gallium, germanium, indium, selenium and tellurium, the new estimates are based on contents in poly-metallic ores, usually that of copper–zinc–lead. Table 3 shows a list of global production rates in the year 2012, the present known recoverable amounts excluding still hidden extractable amounts, estimated recycling rates, yields of extraction and the fractions of total extracted amounts still remaining in the society and being available for recycling.

4. Results

We have organized the results for many different metals into Hubbert's model outputs or WORLD model outputs of peak production and timing of scarcity and interpretation of ramifications and challenges, finalizing with what kind of policy advice we can derive from this. We are looking for several types of outputs:

1. Ultimately recoverable reserves and present recoverable reserves for all major metals.
2. Hubbert's curves for each metal to give the future possible production.
3. Present production and maximum production and stocks in society.
4. The timing of the production maximum and an estimate when scarcity symptoms may become apparent (price rise, price volatility, physical limitations).
5. Possibilities for substitutions to offset scarcity.

Yield information is normally not published anywhere and comes from internal industrial documentation, and they come from a lifelong personal experience with engineering metal processing in the precious metal industry by the authors (Sverdrup). It becomes clear early in this study that we have metals with independent extraction dynamics, and we have metals that depend on the extraction of parent metals, involving several types of poly-metallic ores. Most metals are accumulating in society, in the form of consumables not yet scrapped, technical installations, contained within infrastructures and scrap.

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