Resources, Conservation and Recycling 83 (2014) 121–140

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Investigating the sustainability of the global silver supply, reserves, stocks in society and market price using different approaches☆

Harald Sverdrup[a,*], Deniz Koca[a], Kristin Vala Ragnarsdottir[b]

[a] Applied Systems Analysis and Dynamics Group, Chemical Engineering, Lund University, Box 124, SE-221 00 Lund, Sweden
[b] Institutes of Earth Sciences and Sustainable Development, Askja, University of Iceland, IS-101 Reykjavik, Iceland

ARTICLE INFO

Article history:
Received 4 September 2013
Received in revised form 4 December 2013
Accepted 13 December 2013

Keywords:
Silver
Reserves
Mining
Recycling
Modelling
Sustainability

ABSTRACT

The authors have collected data for the silver market, shedding light on market size, stocks in society and silver flows in society. The world supply from mining, depletion of the remaining reserves, reducing ore grades, market price and turnover of silver was simulated using the SILVER model developed for this study. The model combines mining, trade markets, price mechanisms, populations dynamics, use in society and waste and recycling into an integrated system. At the same time the degree of sustainability and resource time horizon was estimated using different methods such as: 1: burn-off rates, 2: peak discovery early warning, 3: Hubbert's production model, and 4: System dynamic modelling. The Hubbert's model was run for the period of 6000 BC–3000 AD, the SILVER system dynamics model was run for the time range 1840–2340. We have estimated that the ultimately recoverable reserves of silver are in the range 2.7–3.1 million tonne silver at present, of which approximately 1.35–1.46 million tonne have already been mined. The timing estimate range for peak silver production is narrow, in the range 2027–2038, with the best estimate in 2034. By 2240, all silver mines will be nearly empty and exhausted. The outputs from all models converge to emphasize the importance of consistent recycling and the avoidance of irreversible losses to make society more sustainable with respect to silver market supply.

1. Introduction

It is a fact beyond discussion that silver is a limited resource on the globe. Because silver always was rather rare and in short supply, it served as a measure of value. Silver was man's first currency, though in the first millennium of its use as money, it was used in unstandardized units. The silver market is a market within set physical limits and mining production is subject to mass balance limitations. Thus, an integrated assessment of the security of long-term supply and the adequacy of the Earth's silver reserves is of importance for society at large. Gordon et al. (2006), Rauch and Graedel (2007), Greer (2008), Heinberg (2008), Laherrere (2010), Ragnarsdottir (2008), Ragnarsdottir et al. (2011), Sverdrup (2011) and Sverdrup et al. (2013c) expressed concerns about potential scarcity of silver. Silver has been manufactured by humans since at least 3000 BC, first from ores with native silver and later from lead ores. After gold and copper, silver was the third metal for humans to find and work. In modern times, silver is supplied in significant amounts from mining of zinc, lead and copper.

1.1. Hypothesis, objectives and scope

Our hypothesis is that the price of silver and its physical availability can be modelled based on a systemic mapping of silver flows in the world silver trade system, and an assessment will show the risk for shortage of silver expressed as decreased production and increased prices to be significant in the next 30 years. We evaluated the silver supply for the whole globe in a generalized way, and include simulations that cover both the short term and long time into the future, giving simulations covering the time-span of 500 years (1840–2340). To undertake this task for silver, we pulled into the picture the availability of fossil fuels and the size of the human population of the future. This was done by using a preliminary version of a global civilization model presently under development; The WORLD model (Sverdrup et al., 2013c). Previously authors have published some estimates of quantification of when a peak in silver production may occur, but none have ever done any integrated systems modelling on the issue. References of earlier work that we build on include Ragnarsdottir et al. (2011), and Sverdrup et al. (2013c) who gave the peak production year 2032, based on a simple analysis with the Hubbert's peak production model. Roper (2006) published a report on the internet; he gave the peak year

* Corresponding author. Tel.: +46 708855683.
E-mail address: harald.sverdrup@chemeng.lth.se (H. Sverdrup).

0921-3449/$ – see front matter © 2013 The Authors. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.resconrec.2013.12.008

of 2031. Heinberg (2001, 2005, 2011), indicated peaking of silver production between 2030 and 2040, based on burn-off estimates.

2. Methods, theory and definitions

2.1. General

We apply the following fundamental assumptions:

1. The laws of thermodynamics are universally valid, the principles of mass and energy balance apply everywhere with no exception.
2. We assume that the official statistics on reserves in the ground have the correct order of magnitude.

We analyze the system using flow charts based on box-arrow symbols and causal loop diagrams. Many of the data sources are not consistent between them and we will when necessary make expert judgement on what we think is the most likely figures when there are uncertainties.

2.2. Models used

We use several different types of methods in order to estimate the time horizon of a raw material or metal resource scarcity (Ragnarsdottir et al., 2011) by employing these methods:

1. **The burn-off time** is a worst-case scenario, and gives a diagnostic indication for how long the resource will last. It does not consider exponential growth nor market price mechanisms. The burn-off time is defined as the estimated extractable resource divided by the present net yearly extraction rate. This is an accurate estimate in a stagnated economy, but an overestimate in a growing economy. The burn-off is defined as (Ragnarsdottir, 2008; Ragnarsdottir et al., 2011):

$$\text{Burn-off time} = \frac{\text{Known reserves}}{\text{present production}} \quad (1)$$

This gives us a sense of a time-frame until the resource is depleted as a diagnostic variable to evaluate the urgency of the situation at hand.

2. **Peak discovery early warning**. Earlier work has shown that there is a systematic shift of 40 years between the peak discovery and the production peak (Heinberg, 2001, 2005, 2011; Bardi and Pagani, 2008):

$$\text{Peak production time} = \text{Peak discovery time} + 40\text{ years} \quad (2)$$

The gap of 40 years is suggested by Ragnarsdottir et al. (2011) and partially documented by Sverdrup et al. (2013c).

3. **Hubbert's model estimates** of peak production and time to scarcity. The Hubbert's curve is defined by the simple equation for cumulative production (Hubbert, 1966, 1972, 1982; Bardi and Yaxley, 2005; Sverdrup et al., 2013c):

$$m(t) = \frac{\text{URR}}{1 + e^{-b\times(t-t_{\text{MAX}})}} \quad (3)$$

where m is the sum of all resource produced to time t, and t_{max} is the time of the peak production, URR is the size of the whole resource, and b is the curve shape constant. The annual production is given by:

$$P(t) = \frac{2\times P_{\text{MAX}}}{1+\cosh\ (b\times(t-t_{\text{MAX}}))} = \frac{1}{2\times b}\times\frac{\text{URR}}{1+\cosh\ (b\times(t-t_{\text{MAX}}))} \quad (4)$$

where P_{MAX} is the maximum production rate, $P(t)$ is the production at time t. If we can distinguish several independent reserves or groups of reserves, these may be modelled individually and the results summed up at the end. The curve will be consistent with the reserve estimates. The amount mined until now is given by the integral of Eq. (3):

$$m(t) = \int_0^t P(t)dt = \frac{4\times P_{\text{MAX}}}{b\times(1+e^{-b\times(t-t_{\text{MAX}})})} \quad (5)$$

This may be turned around to yield the estimation for the time of the peak if we know the overall average b and the maximum production or the ultimately recoverable amount (URR) of the resource:

$$t_{\text{MAX}} = t_{\text{NOW}} + \frac{1}{b}\ln\left(\frac{4\times P_{\text{MAX}}}{\text{b}\times m_{\text{NOW}}} - 1\right) = t_{\text{NOW}} + \frac{1}{b}\ln\left(\frac{\text{URR}}{m_{\text{NOW}}} - 1\right) \quad (6)$$

The estimate of t_{MAX} is sensitive to the accuracy of the estimate of b. URR is given by:

$$\text{URR} = 4\times\frac{P_{\text{MAX}}}{b} \quad (7)$$

In case n curves are used to generate the full cumulative production curve, we get as illustrated in Fig. 1:

$$m(t) = \sum_{i=1}^{i=n} m_i(t) = \sum_{i=1}^{i=n}\frac{\text{URR}_i}{1+e^{-b\times(t-t_{\text{MAX},i})}} \quad (8)$$

and for the total URR:

$$\text{URR} = \sum_{i=1}^{i=n}\text{URR}_i = \sum_{i=1}^{i=n}\frac{4\times P_{\text{Max},i}}{b_i} \quad (9)$$

The peak time must be determined from the maximum among the different local production maxima available under the assumption that this is the overall maximum production; this is found by a rearrangement of Eq. (5):

$$t_{\text{MAX}} = t_{\text{NOW}} + \frac{1}{b}\ln\left(\frac{4\times\max[P_{\text{MAX},i}]}{b\times m_{\text{NOW}}} - 1\right) = t_{\text{NOW}} + \frac{1}{b}\ln\left(\frac{4\times\max[P_{\text{MAX},i}]}{b\times m_{\text{NOW}}} - 1\right) \quad (10)$$

If we cannot set b accurately with one curve, then t_{MAX} must be graphically determined by curve-fitting. The composite curves drawn in this study are adjusted so that the amounts under the curves correspond to the best estimate of the Ultimately Recoverable Reserve (URR). Fig. 1 illustrates how the curve for silver was constructed using a Hubbert's function several times and adding them up as is shown in the figure.

4. **System dynamic modelling** was used to reconstruct the past for explanatory and testing purposes, to estimate the time to production maximum, and to study the rate of decline to silver scarcity after the maximum production rate has been passed. The flow pathways and the causal chains and feedbacks loops in the system are mapped using systems analysis, and then the resulting coupled differential equations are transferred to computer codes for numerical solutions, using an environment such as STELLA®. The methods are those of systems analysis and systems dynamics, incorporating mathematical modelling of complex systems (Senge, 1990; Sterman, 2000; Haraldsson and Sverdrup, 2004; Meadows et al., 1972, 1992, 2005; Sverdrup et al. 2013a,b,c). This approach gives more detail, demands more insight and can include more factors, but is more difficult to parameterize. For dynamic modelling, elaborate flow chart and causal loop systems analysis charts are needed.