Resources, Conservation and Recycling 87 (2014) 158–174

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

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

On modelling the global copper mining rates, market supply, copper price and the end of copper reserves

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

[a] Industrial Engineering, University of Iceland, VR-II, Hjardahagi 2-6, IS-107 Reyjavik, Iceland
[b] Institutes of Earth Sciences and Sustainability Studies, University of Iceland, IS-101 Reykjavik, Iceland
[c] Applied Systems Analysis and Systems Dynamics Group, Chemical Engineering, Lund University, Box 124, SE-221 00 Lund, Sweden

ARTICLE INFO

Article history:
Received 26 August 2013
Received in revised form 14 March 2014
Accepted 19 March 2014
Available online 10 May 2014

Keywords:
Copper
Price
Reserves
Mining
Recycling
Dynamic modelling
Sustainability

ABSTRACT

The world supply and turnover of copper was modelled using simple empirical estimates and a COPPER systems dynamics model developed for this study. The model combines mining, trade markets, price mechanisms, population dynamics, use in society and waste as well as recycling, into a whole world system. The degree of sustainability and resource time horizon was estimated using four different methods including (1) burn-off rates, (2) peak discovery early warning, (3) Hubbert's production model, and (4) COPPER, a system dynamics model. The ultimately recoverable reserves (URR) have been estimated using different sources that converge around 2800 million tonne, where about 800 million tonne have already been mined, and 2000 million tonne remain. The different methods independently suggest peak copper mine production in the near future. The model was run for a longer period to cover all systems dynamics and delays. The peak production estimates are in a narrow window in time, from 2031 to 2042, with the best model estimate in 2034, or 21 years from the date of writing. In a longer perspective, taking into account price and recycling, the supply of copper to society is estimated to run out sometime after 2400. The outputs from all models put focus on the importance of copper recycling so that society can become more sustainable with respect to copper supply.

1. Introduction

Like other metals, copper is a limited resource on the Earth. It is undebatable that copper is one of the most important metals for modern society, ranking after iron and aluminium in importance for infrastructure and technology. The copper market is affected by the fact that it is traded in a free market within set physical limits and that production is subject to mass balance limitations. Thus, an integrated assessment of the security of long-term copper supply and the adequacy of the Earth's copper reserves are of interest (Hall et al., 2001; Heinberg, 2001; Johnson et al., 2007; Jackson, 2009; Distelkamp et al., 2010; Graedel et al., 2004, 2011; Meyer et al., 2012a; Bleischwitz et al., 2012; Turner, 2009, 2012). The largest users of refined copper are the energy sector and the building industry. In Europe, copper use is broken down as follows: Electricity and energy: 58%, building and construction: 26%, industrial plant and machinery, furniture, coinage: 10%, and transport: 5% (Rauch and Graedel, 2007). We are not the first to be concerned about the global sufficiency of copper; recently Gordon et al. (2006), Rauch and Graedel (2007), Bardi and Pagani (2008), Heinberg (2011), and Laherrere (2010) presented copper analyses and expressed worries about a potential scarcity or future peak in production. Further recent estimates are found in reports by the International Resource Panel (UNEP/IRP) (The International Resource Panel, 2011, 2012, 2013). The IRP report from 2013 discusses recycling of metals in many aspects and is a very valuable synthesis of state-of-the-art. However, the IRP reports do neither assess remaining reserves nor the prospects that exhaustion may occur.

2. Objectives and scope

Today, the three most important strategic metals for human society are recognized to be iron, aluminium, zinc and copper. Our goal was to develop an integrated dynamic model for the global copper market, simulating market supply, production rates, market price and to predict how the known and hidden resources will

* Corresponding author. Tel.: +46 708 855 683.
E-mail addresses: Harald.sverdrup@chemeng.lth.se (H.U. Sverdrup), vala@hi.is (K.V. Ragnarsdottir), Deniz.koca@chemeng.lth.se (D. Koca).

http://dx.doi.org/10.1016/j.resconrec.2014.03.007
0921-3449/

be used. The hypothesis is that by using mass balance-based model, we can reasonably reconstruct the past from our understanding of the copper system and the data we have available. The objective is to use the validated model to explore the system and make future predictions about how to make the copper system more sustainable. This included conducting systemic mapping of copper flows in the world copper trade system, and finding the necessary parameters for such a model. In this paper we present copper mining, recycling, supply and demand, as well as market price as derived dynamically from parameters in the model. We included the whole globe in a generalized way; simulations cover the recent past and immediate future (next ten decades), as well as a long time perspective of a thousand years. Our focus in this study is copper, but we pull into the picture the availability of fossil fuels as well as the predicted future human population. This was undertaken by using a preliminary version of a global civilization model presently under development: The WORLD Model (Sverdrup et al., 2013), and learning from the experiences of other metal models (Sverdrup et al., 2014).

3. Theory and model descriptions

3.1. General principles applied in the modelling

In this study we apply the following fundamental assumptions:

1. The laws of thermodynamics are universally valid, and that the principles of mass and energy balance apply everywhere with no exception.
2. We assume that the official statistics for copper reserves in rock formations have the correct order of magnitude.
3. Copper is sold as the physical metal and we ignore the derivatives trade in our economics model and the price mechanism.

We use four methods in this study to estimate the time horizon of a raw material or metal resource (Ragnarsdottir et al., 2012): (1) calculation of burnoff time, (2) the relationship between peak discovery and early warning, (3) calculations of Hubbert' peak production curves and (4) system analysis and system dynamics that incorporates mathematical modelling of complex systems.

1. *The Burn-off time* is a worst-case scenario, and gives a worst-case estimate (Ragnarsdottir et al., 2012). 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 extraction rate. This is an accurate estimate in a stagnated economy, but an overestimate in a growing economy and increasing population.

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

This gives a sense of a time-frame as a diagnostic variable to evaluate the urgency of today' situation.

2. *Peak discovery early warning*. Earlier work has shown that there is a systematic shift of 40 years between the peak discovery of a natural resource and the production peak. A survey of peak discovery and relating that to peak production, suggest that there is for oil, coal, copper, gold and silver, a 40-year lag between discovery peak and the production peak (Sverdrup et al., 2011; Ragnarsdottir et al., 2011, 2012; Sverdrup et al., 2013, 2014). Thus we have:

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

3. *Modified Hubbert's-curve estimates* of peak production and time to scarcity. The Hubbert's curve is defined by the simple equation for cumulative production. The annual production is given by:

$$P = \frac{2 * P_{\max}}{(1 + \cosh(b * (t - t_{\max})))} \quad (3)$$

where $P_{\max}$ is the maximum production rate, P_t is the production (P) at time t, $t_{\max}$ is the time of the peak, and the coefficient b is the curve shape constant. The ultimately recoverable reserves (URR), is given by:

$$\text{URR} = \frac{4 * P_{\max}}{b} \quad (4)$$

The Hubbert's curve model is robustly verified on field data for oil, coal, phosphorus and metal mining, demonstrating that it works well for all natural resources (Bartlett, 1999; Hubbert, 1966, 1972, 1982; Greene et al., 2005; Cavallo, 2004; Hirsch et al., 2005; Bardi and Yaxley, 2005; Sverdrup et al., 2013, 2014). The curve drawing in this study is adjusted so that the amount under the curve corresponds to the URR, so that the curve is consistent with the reserve estimates. Exponential growth and market price mechanisms are empirically captured into the Hubbert's estimate in a lumped way. The method is well field validated, and gives reliable estimates.

(4) *System dynamics modelling* was used to estimate the time to scarcity as time for the known reserves of high grade and low grade to have decreased to 10% of the maximum production rate. Here we analyze the copper system using flow charts based on box-arrow symbols, causal loop diagrams and mathematical modelling using the STELLA® system. The available data was closely inspected for inconsistencies and averages and adjustments were made when the input data were not internally consistent. Many of the sources we use are inconsistent and there we make expert judgement about what are the most likely figures. We use the causal loop diagrams (CLD) for reading out where the intervention points in the system are, and to propose policy interventions. The COPPER model simulations are used for quantifications. System dynamics modelling The flow pathways and the causal chains and feedbacks loops in the system are mapped using system analysis, and then the resulting coupled differential equations are transferred to computer codes for numerical solutions, using an environment such as STELLA®. This method gives more detail, demands more insight and can include more factors including recycling rates and prizing, but it is more difficult to parameterize than methods 1–3 (Forrester, 1971; Haraldsson and Sverdrup, 2004; Haraldsson et al., 2007; Meadows et al., 1993, 2005).

Of these methods, we use 1–3 to give us diagnostic indicators of fundamental and substantial copper scarcity problems in the future. Method number 4 is used for predictions. When our findings show that the basic assumptions of boundary conditions are no longer valid, then static methods like 1–2 are no longer usable and econometric models are no longer valid, and cannot be used for predictions. Then fully integrated, process and mechanism-oriented system dynamic models are required. Process-oriented systems dynamic models are the only type of models that allow with reasonability predictions to be made for the future.

3.2. Input data for the models and the assumptions made to fill gaps

Tables 1–7 show the data used as inputs to parameterization of the models used in the assessment. The estimated cumulative