Global Environmental Change 39 (2016) 305–315

Contents lists available at ScienceDirect

Global Environmental Change

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

Copper demand, supply, and associated energy use to 2050

Ayman Elshkaki*, T.E. Graedel, Luca Ciacci, Barbara K. Reck

Center for Industrial Ecology, School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511, USA

ARTICLE INFO

Article history:
Received 21 October 2015
Received in revised form 30 May 2016
Accepted 7 June 2016
Available online 22 June 2016

Keywords:
Copper
Resources
Energy
Scenario analysis
Dynamic modelling

ABSTRACT

To a set of well-regarded international scenarios (UNEP's GEO-4), we have added consideration of the demand, supply, and energy implications related to copper production and use over the period 2010–2050. To our knowledge, these are the first comprehensive metal supply and demand scenarios to be developed. We find that copper demand increases by between 275 and 350% by 2050, depending on the scenario. The scenario with the highest prospective demand is not Market First (a "business as usual" vision), but Equitability First, a scenario of transition to a world of more equitable values and institutions. These copper demands exceed projected copper mineral resources by mid-century and thereafter. Energy demand for copper production also demonstrates strong increases, rising to as much as 2.4% of projected 2050 overall global energy demand. We investigate possible policy responses to these results, concluding that improving the efficiency of the copper cycle and encouraging the development of copper-free energy distribution on the demand side, and improving copper recycling rates on the supply side are the most promising of the possible options. Improving energy efficiency in primary copper production would lead to a reduction in the energy demand by 0.5% of projected 2050 overall global energy demand. In addition, encouraging the shift towards renewable technologies is important to minimize the impacts associated with copper production.

1. Introduction

Copper is one of the most widely-used metals in society. Due to its unique properties copper is essential for several economic sectors, including infrastructure, wiring, plumbing, transportation, and consumer and industrial electrical and electronic equipment (EEE). In recent years, the demand for copper has grown rapidly (USGS, 2009) as a result of the increasing global population, economic growth (especially in emerging economies), and the transition to a more sustainable society. This growth in copper demand is higher than the increasing supply of copper from secondary resources, explaining the growing demand for primary copper (ICSG, 2006, cited in Gomez et al., 2007; ICSG, 2012, 2015). This has raised concern regarding the future availability of copper and its companion metals including tellurium, selenium, silver, cobalt, and molybdenum, which are necessary for construction activities as well as for the transition to sustainable energy, transportation, and industrial systems (Elshkaki and Graedel, 2015; Nassar et al., 2012, 2015).

In addition to resource availability concerns, there is increasing concern related to the energy requirement to produce metals and to the associated environmental impacts. The mining industry is one of the most energy-intensive industrial sectors, and thus one of the largest contributors to global CO_2 emissions. This is mainly due to the amount of metals produced and the low concentration of most metals in ore deposits, which led to the mining of large quantities of the ore. The global energy consumption for the principal primary metals (iron, aluminum, copper, manganese, zinc, lead) has increased from 32 EJ/y in 2007–52 EJ/y in 2012 (Norgate and Jahanshahi, 2011), which is about 10% of the total 2012 primary energy production (Fizaine and Court, 2015). Copper is one of the metals whose production is highly energy intensive, and consequently has high environmental impacts. In Chile, the world's largest copper producing country, the copper industry is by far the largest energy consumer and the largest GHG emitter (Alvarado et al., 2002). As the demand for copper increases, its ore grade is expected to decrease, and the energy required for copper production and the related CO_2 emissions are thus expected to increase fairly rapidly (Ayres et al., 2001; Kuckshinrichs et al., 2007; Mudd, 2010; Northey et al., 2014; Valero and Valero, 2014).

Several studies have attempted to assess the future demand for a number of different metals (Allwood, 2014; Elshkaki et al., 2005; Elshkaki and Van der Voet, 2006; Gerst, 2009; Halada et al., 2008;

* Corresponding author.
E-mail addresses: ayman.elshkaki@yale.edu, elshkaki@gmail.com (A. Elshkaki).

http://dx.doi.org/10.1016/j.gloenvcha.2016.06.006
0959-3780/

Hatayama et al., 2010; Kleijn and van der Voet, 2010 (who find a potential supply limitation for copper due to renewable energy deployment); Liu et al., 2013; Pauliuk et al., 2012; Stamp et al., 2014; Van der Voet et al., 2002; Van Vuuren et al., 1999). However, these metal demand scenarios tend to be limited to a focus on specific technologies rather than on more general uses. In addition, none follow from a foundational set of scenarios generated by specialists in such disciplines as demography, economics, and assessments of industrial limitations and opportunities. Thus, there remains a need for scenario approaches to metal futures that emphasize breadth in the choice of metals and employ a widely recognized family of scenarios as a starting point.

In the present study, we develop four scenarios for the global demand for copper, the global and regional supply of copper, and the energy required for primary and secondary copper production. The foundation for these metal scenarios is the Fourth Global Environmental Outlook (GEO-4) set of scenarios of the United Nations Environment Program, which are based on the Global Scenario Group (GSG) approaches and related scenarios (Jan Bakkes et al., 2004; Electris et al., 2009; Kemp-Benedict et al., 2002; UNEP, 2007). A detailed discussion of the GEO scenarios and comparison with other scenarios can be found in Raskin et al. (2005) and Van Vuuren et al. (2012). The GEO-4 scenarios, termed Market First (MF), Policy First (PF), Security First (SF), and Equitability First (EF), are briefly described in Box 1. Each includes global and regional projections of population, per capita income, and source-specific energy demand. These well-vetted scenarios have been extensively employed in the past at global and regional levels to examine possible futures of such variables as atmospheric emissions, food availability, water withdrawals, and species abundance changes (UNEP, 2006, 2007, 2010; Van Vuuren et al., 2012). To those scenarios we add copper-relevant technology demand, primary and secondary copper supply, and related energy use. The period of study is 2010–2050, with one year time resolution.

2. Methodology

2.1. Copper demand

Regression analysis is used in many scientific fields as a statistical tool to estimate and analyze the relation between a dependent variable and a number of independent, explanatory variables. It identifies the variables that are significant and that contribute the most to the dependent variable. The approach further examines the separate and combined effects of significant variables. The optimal regression model, the adequacy of the model, and the significance of the variables are traditionally described by several statistical parameters: the coefficient of determination (R^2), the adjusted coefficient of determination (R^2adj), and the t- and F- statistics.

We carried out the analysis of the historical demand for copper from 1980 to 2010 using regression analysis with per capita GDP, the level of urbanization, and time as explanatory variables. Time is used as a proxy for such time-dependent variables as policy changes, substitution, and technological development. The form of the regression equation is

$$Y(t) = \alpha_0 + \sum_{i=1}^{n} \alpha_i X_i(t) + \varepsilon(t) \tag{1}$$

where $Y(t)$ is the inflow of metals into the stock-in-use at time t, n is the number of explanatory variables, $X_i(t)$ are the explanatory variables at time t, α_i are the regression model parameters and $\varepsilon(t)$ is the residuals of the regression model.

The linear regression model is used in this analysis to find the optimal model for the total historical demand for copper and its use in each major copper-relevant industrial sector. Data for the total demand for copper and its demand in nine sectors is estimated based on information collected from different sources and shown in Fig. 1(a) (USGS, 1932–2011; Spatari et al., 2005; Nassar et al., 2012). GDP/capita is estimated using GDP at purchasing power parity (constant 2005 international $) and population records from the World Data Bank (World Bank, 2015). The level of urbanization, which represents the share of inhabitants living in urban areas as per cent of total population, is also estimated using World Data Bank population records, together with urban ratios from the United Nations World Urbanization Prospects (World Bank, 2015; United Nations, 2015).

It is, of course, true that if and when a resource of any kind becomes scarce, its price is likely to rise rapidly and demand would thereby decrease accordingly. In the case of copper, a decrease in demand would likely result in an inability to respond efficiently to the needs for the services that copper provides, such as efficient conductance of electricity. All such demand-supply-economic systems are demonstrably non-linear, and some researchers (e.g., Sverdrup et al., 2014) have attempted to model metal futures in a non-linear fashion. In the absence of a firm basis from which to specify such non-linearities, however, we choose instead to model copper demand as a function of widely-regarded expert assessments of likely population growth, per capita income, and level of urbanization under different types of global development (see above). Time is included as an additional variable to capture other possible historic variables such as substitution, technological development and policy changes. We then compare the demand results to detailed predictions of primary and secondary copper supply to identify situations in which future demand may or may not be able to be met by available supply, and to identify the implications of declining ore grade and enhanced energy demand.

2.2. Copper supply

The demand for copper is met by the supply from primary and secondary (recycled) sources. The historical supply of copper from secondary sources and its contribution to total copper demand are shown in Figs. Fig. 1(b) and (c) (ICSG, 2006, cited in Gomez et al., 2007; ICSG, 2012, 2015). The fraction of copper demand that can be

Box 1. Brief "storylines" of the UNEP GEO-4 foundational scenarios

Market First (MF). A market-driven world in which demographic, economic, environmental, and technological trends unfold without major surprise relative to currently unfolding trends.
Policy First (PF). A world in which strong actions are undertaken by governments in an attempt to reach specific social and environmental goals, especially as pertains to renewable energy.
Security First (SF). A world of great disparities where inequality and conflict prevail, brought about by socio-economic an environmental stresses.
Equitability First (EF). A world in which a new development paradigm emerges in response to the challenge of sustainability, supported by new, more equitable values and institutions.