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Anthropogenic nickel supply, demand, and associated energy and water use

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ABSTRACT

Concerns about the long-run availability of metals have led to speculation that resources that have traditionally been available may become increasingly scarce in the future. To investigate this possibility in the case of nickel, we have built upon the history of nickel flows into use for the period 1988 to the present to develop plausible scenarios for the potential future supply and demand of nickel for the planet, and the associated energy and water use. As in other work, these scenarios are not predictions, but rather stories of possible futures that have the purpose of providing perspective and contemplating policy options. We report herein on our results for nickel supply and demand under four scenarios. We find that calculated nickel demand increases by 140–175% by 2025 and 215–350% by 2050, depending on the scenario. The scenario with the highest prospective demand is termed *Equitability World*, a scenario of transition to a world of more equitable values and institutions. From the perspective of the results for the four scenarios, we conclude that nickel demands could be met until at least 2050 given known geological nickel resources. The energy and water required for nickel production are anticipated to increase to as much as 0.3% and 0.035% of projected 2050 overall global energy and water demands.

1. Introduction

Metals are used in most modern technologies either as necessary constituents or to enhance technological efficiencies. Nickel is among the metals used extensively in a number of important applications, including buildings and infrastructure, transportation, industrial machinery, appliances, and metals goods. In these uses, often in the form of stainless steel or superalloys, nickel's corrosion resistance, strength, and high-temperature stability are particularly valued. In recent years increases in global population and economic growth have been associated with an increase in the demand for metals. (Nickel production more than doubled in the past 20 years (from 1040 Gg in 1995–2280 Gg in 2015 (USGS, 1997; USGS, 2017). Concerns about the long-run availability of metals have led to speculation that nickel resources that have traditionally been available may become increasingly scarce in the future (e.g., Yang, 2009; Kerr, 2012).

Economic nickel resources are found in two types of ores: sulfides and laterites. Nickel resources have traditionally been primarily produced from sulfide ores. With increasing demand, however, an increasing amount is being produced from laterite ores, leading to an increase in the energy and greenhouse gas emissions associated with nickel production due to the more complex processing required for laterites (Mudd, 2010). In addition, there is concern related to the energy and water requirements to produce metals (Norgate, 2010), and to the associated environmental impacts (UNEP, 2013). In this regard, the global energy consumption for the principal primary metals (iron, aluminum, copper, manganese, zinc, lead, and nickel) is currently (2012) about 10% of the total primary energy production (Fizaine and Court, 2015).

A number of previous scenario studies have attempted to assess the future demand for metals (Binder et al., 2006; van der Voet et al., 2002; Elshkaki et al., 2005; Gerst, 2009; Hatayama et al., 2010; McLellan et al., 2016; Pauliuk et al., 2012; Liu et al., 2013; Elshkaki and Van der Voet, 2006; Stamp et al., 2014). Many of these researches have, however, been limited in their general emphasis 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.

In this paper, in contrast, we investigate the potential future supply and demand for all principal uses of nickel and the associated energy and water use, based on the history of nickel flows into use for the period 1988 to the present. As in other work, the resulting scenarios are not predictions, but rather stories of possible futures. Their purpose is to provide perspective and contemplate policy initiatives that respond to developmental alternatives. The four scenarios are described in some detail in the Supplementary Information. In brief, however, the *Market World* scenario essentially posits that the newly wealthy will wish to acquire possessions similar to those of the existing wealthy, and that market forces will enable that to happen. The *Toward Resilience* scenario

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is similar except that government policies more respectful of renewable energy and the environment will be in force, with potential implications for related material demand. The *Security Foremost* scenario tilts toward confrontation rather than cooperation, with a consequent reduction in international commerce. Finally, the *Equitability World* scenario aims toward a more collaborative and inclusive world. This latter scenario is the one most closely aligned with the UN Sustainable Development Goals (United Nations, 2015).

2. Methodology

2.1. Historic nickel demand

The use of nickel for industrial, commercial, and consumer purposes is widespread in the global economy, and has been so for a number of decades (Reck et al., 2008). Nickel's major uses have significant technological momentum, and a substantial degree of substitution by other metals over the short and medium terms is unlikely (Graedel et al., 2015). In situations such as this, where the past appears to be a reasonably reliable guide to the future, regression analysis is a useful starting point. The technique is used in many scientific fields as a statistical approach to estimate and analyze the relationship between a dependent variable and a number of independent, explanatory variables. It identifies the independent 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.

Historical nickel flows into use are determined based on the demand for nickel in different end use sectors in different world regions (Fig. 1). We draw upon the United Nations GEO4 scenarios (UNEP, 2007; Electris et al., 2009) for demographic and economic perspectives on the future, and the International Energy Agency (2012) for energy mix and energy demand alternatives. GDP/capita is computed 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 a per cent of total population, is also derived from World Data Bank population records, together with urban ratios from the United Nations World Urbanization Prospects (UN Habitat, 2013; World Bank, 2015).

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 values. 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 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 (cf. Roberts, 1996; Guzman et al., 2005). Per capita GDP acknowledges that the rates of use of several metals have been shown to be proportional to per capita GDP (Binder et al., 2006; Rauch, 2009). The level of urbanization is used as a potential independent variable because urbanization is strongly related to housing and infrastructure, which are major uses of nickel. The form of the regression equation is

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

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 variable values at time t, α_i are the regression model parameters, and $\varepsilon(t)$ is the residuals of the regression model.

The historical demand for nickel, and its demand as estimated by the models obtained by regression analysis for each sector, are shown in Fig. S1 in the Supporting Information.The resultant correlations between historic nickel demand and its demand in different industrial sectors are listed in Table 1, together with the explanatory variables that are used in the four scenarios. As can be seen from the table, the historical nickel use patterns are completely explained by GDP/capita, a result consistent with that of Shigetomi et al. (2017).

Our goal in this work is to examine the long-term prospects for nickel rather than to focus on monthly or yearly demand variations. As a consequence of this goal, and because there is no evidence that metal prices reflect longer-term scarcity in any way (Henckens et al., 2016), we do not employ economic or systems dynamic approaches that might be quite useful in studies with a shorter-term focus.

2.2. Historic and future nickel supply

It is important to realize that the demand for nickel is met by primary and secondary (recycled) sources. The historical contribution of nickel supply from secondary sources has typically been about 30% of total nickel demand (Fig. 2). The fraction of nickel demand that can be met by the supply from secondary sources is determined by the historical nickel demand, the lifetime of nickel applications, and nickel

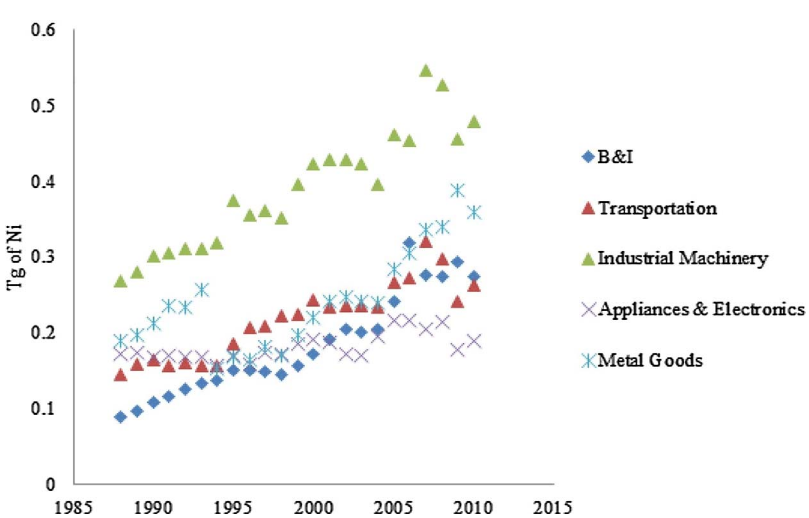

Fig. 1. Historic global level flows into use of nickel in its principal applications. B & I = buildings and infrastructure. The data are updates from Reck & Rotter (2012).