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Metal supply constraints for a low-carbon economy?

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A B S T R A C T

Low-carbon energy systems are more metal-intensive than traditional energy systems. Concerns have been expressed that this may hamper the transition to a low-carbon economy. We estimate the required extraction of Fe, Al, Cu, Ni, Cr, In, Nd, Dy, Li, Zn, and Pb until 2050 under several technology-specific low-carbon scenarios. Annual metal demand for the electricity and road transportation systems may rise dramatically for indium, neodymium, dysprosium, and lithium, by factors of more than three orders of magnitude. However, in the base year 2000 the dominant uses were often in other sectors. Since growth in these other, previously dominant sectors has been less pronounced, the overall growth in society's metal needs is much less dramatic than in the electricity and transportation sectors. Total annual demand for the researched metals would rise by a factor of 3–4.5, corresponding to compound growth rates of between 2% and 3%. Such growth rates are similar or lower compared with historical growth rate levels over the last few decades. Prolonged higher levels have existed for copper, for example, with production rising by 8% per year from 1992 to 2006. Yet this state of affairs does not give cause for complacency. The richest resources may have been used, production is showing a tendency towards becoming very large-scale, and development times have increased, all leading to greater risks of disruption. It is therefore crucial, when developing specific technologies, that the resource-specific constraints are analyzed and options for substitution are developed where risks are high.

1. Introduction

Low-carbon energy systems are considerably more metal-intensive than traditional energy systems, and authors have warned that this may hamper the transition to a low-carbon economy (Alonso et al., 2012). Especially assessments focusing on the implementation of low-carbon technologies in the energy and transportation sectors show a dramatic increase in the metal demands of those sectors (Kleijn et al., 2011; Roelich et al., 2014). For some metals it has been reported that the rapid increase in demand is not problematic. Availability of Lithium, currently an essential element for electric vehicle batteries, is not expected to be a bottleneck for the rapid and widespread adoption of electric vehicles (Gruber et al., 2011). On the basis of a dynamic material flow model for the base metals aluminum, copper, chromium, nickel, lead, and iron, Elshkaki and Graedel (2013) found that supply is not limiting the introduction of renewable electricity generation technologies. On the other hand, they found that constraints in the supply of silver, tellurium, indium, and germanium could limit the introduction of some PV technologies (Elshkaki and Graedel, 2013). Most of these studies, however, did not take into account that the additional demand for low-carbon technologies should be considered in the context of a general increase in primary production of these metals for the entire economic system, also in relation to the build-up of infrastructure in newly developing countries.

This paper investigates potential bottlenecks in the supply of a wide range of metals, assuming the gradual introduction of far-reaching climate policies leading to full global implementation by 2050. We use a novel combination of methodologies, covering both the power generation and automotive sectors in detail and the broader economy more generally.

The novel aspect of our method is that specific data on the metal requirements for low-carbon energy and energy technologies are analyzed in combination with long-term socio-economic scenarios implemented in a global multi-regional Input-Output model, which captures the global metal requirements and global greenhouse gas emissions of the global economy. This allows us to create a consistent scenario of metal demand and greenhouse gas (GHG) emissions. For instance, if mining of a particular metal increases, there will be an

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increase in the amount of machinery needed for the mining sector, and also in the associated electricity production (and hence GHG emissions) for making that machinery.

A key consideration in developing this methodology is that the future supply and demand of metals cannot really be predicted. There is uncertainty about how energy technologies will develop and what their metal requirements will be. Different scenarios with different assumptions concerning the penetration of low-carbon energy technologies can be envisaged (IPCC, 2014; IEA, 2008; OECD, 2012a,b). It is unknown if new options for substitution between metals and with other materials will become available. Recent examples of this are the current shift in plumbing from copper to polymers and aluminum (TEPPFA, 2013; Hix and Seydel, 2016), and the way some automobile and wind turbine producers avoided using neodymium when its prices spiked in 2011 (ENERCON, 2011; Tukker, 2014; Widmer et al., 2015). How the supply of metals may develop is also unknown. The main supply constraint is that a metal must be mined economically. The actual long-term supply of metals is highly dependent on new (mining) technology, cumulative availability curves, and expected and actual prices (Tilton and Lagos, 2007; Yaksic and Tilton, 2009; Gordon et al., 2007). Expected prices determine investment in mines, for given funding options and within political constraints.

The metals that we were able to analyze with the global multi-regional scenario model were Fe, Al, Cu, Ni, Cr, In, Nd, Dy, Li, Zn, and Pb. In the case of other metals, data on their extraction, reserves and use were insufficient to make a full analysis, as we did for the eleven selected metals.

2. Materials and methods

Long-term scenarios for supply and demand of metals are difficult to make. This is particularly true for minor metals such as In, Nd, Dy, and Li. New high-tech technologies can lead to disruptive demand change in just a few years, while it can take 10 years or more to adjust production and open new mines (Tukker, 2014). In this paper we try to deal with this unpredictability by analyzing whether various contrasting scenarios for metal demand fall within a 'viable operating space' with regard to supply. We define this viable operating space as a situation where, in view of knowledge about economic reserves and past supply growth rate, the supply can in principle meet the demand in the scenarios. If expected demand for a metal falls outside this operating space, this strongly suggests a risk of steep price rises. In that case, consideration should be given to developing material substitutes or alternative technologies, or opening up new mining options.

The proposed concept of viable operating space for metal supply and demand is based on the following information: (a) estimated annual demand for metals in 2050 in a given scenario; (b) annual supply of metals in 2000; (c) historical growth rates of this metal supply; (d) estimated cumulative metal demand until 2050 in a given scenario; (e) estimated economic reserves in 2000, and (f) historical growth rates of these reserves. The assumption is that supply problems are likely to occur if demand growth for a metal will be much higher in the future than in the past, and/or if the cumulative requirements until 2050 are significantly higher than the economic reserves in 2000, including the observed historical growth rates of these reserves. These extrapolated supply quantities and reserve volumes thus act as upper boundaries of the viable operating space (see Fig. 1 for a conceptual graphical explanation). This allows us to compare these boundaries with scenarios for the rise required by the expected demand for metals in 2050 in relation to supply in 2000, and to compare the current economic reserves with the expected cumulative metal demand until 2050. With this information, we can make an overall assessment of potential bottlenecks in the supply of metal resources due to effective climate policy, or in positive terms: define the viable operating space.

It should be noted, however, that although our concept can give a clear indication of future supply problems, it also has limitations. A significant increase in demand could lead to substantial price rises, which in turn would increase economic reserves: reserves that had been too costly to mine can be extracted profitably at these higher prices. We did not take this into account. But conversely, our approach also takes no account of potential absolute limits to metal availability. While most of the recent metal supply crises were related to disruptive demand changes (e.g. Tukker, 2014; ERECON, 2015; Sprecher et al., 2015), which are factors covered by our concept, in the longer term such absolute scarcity problems could also play a significant role. We therefore regard the boundaries derived from our concept as 'upper boundaries'. Whereas the actual supply rate (amount mined) of metals is quite well known in 2000, there is less information about the economic reserves of metals in 2000. Published estimates of economic reserves can vary considerably and change rapidly, as shown by Gruber et al. (2011) for Lithium. All the economic reserve data have been derived from the USGS (Kelly and Matos, 2009).

Different supply scenarios can be envisaged on the basis of cumulative supply curves and real prices, but such an was not carried out in this study for two reasons. First, cumulative supply curves are uncertain or unknown for the metals considered in this study. Second, cumulative supply curves are only valid for currently known mining technology; the cumulative supply curve shifts if cost-reducing technology changes take place (Yaksic and Tilton, 2009).

As stated above, the demand for the eleven metals in 2050 in the four scenarios is estimated by combining two methodologies. Global metal requirements for low-carbon electricity and road transportation systems are calculated from appropriately scaled Life Cycle Assessment (LCA) inventories. Estimates for metal consumption in the rest of the economy are based on a global multi-regional extended Input-Output (IO) model, combined with expected GDP growth and extrapolation of general historical efficiency improvements and specific changes in energy intensive activities (steel production, cement production, built environment, domestic appliances). The metal requirements are based on three scenarios superimposed on a business-as-usual scenario, making a total of four scenarios. They are:

1) **Business-as-usual (BAU) scenario**, on an 8° path. We based our BAU scenario on historical developments, including efficiency improvements, extrapolated until 2050 (de Koning et al., 2014, 2016). The GDP development in the BAU scenario, like all the other scenarios below, follows projections by the OECD (OECD, 2012b). It appears that the GHG emissions in the BAU scenario constructed in this way are on a trajectory towards 8 ° of global warming in 2100, similar to the RCP8.5 BAU scenario (IPCC, 2014; de Koning et al., 2014).
2) **Technological Scenario (TS)**, on a 4° path. The second scenario is a Techno Scenario (TS), which integrates all probable and possible technical CO_2 emission reduction measures currently envisaged. It is a techno-optimistic scenario and includes, for instance, carbon capture and storage (CCS) on all the remaining fossil fuel power plants, widespread introduction of electric vehicles and complete electrification of household heating. The TS brings us onto a trajectory of about 4 ° of global warming, similar to the RCP4.5 scenario (IPCC, 2014). GDP growth in the TS also follows projections made by the OECD (OECD, 2012b).
3) **Blue Map electricity supply (BMES) scenario** of IEA, on a 4° path. The third scenario is similar to the TS scenario except that the global electricity supply mix in 2050 is taken from the IEA Blue Map scenario (IEA, 2008), with 23% nuclear, 26% fossil with CCS, and 44% renewables. The IEA Blue Map scenario suggests that by 2050 global energy CO_2 emissions would be halved compared with 2005 emissions, which would put average global temperature increase on a trajectory of 2–3 °C above pre-industrial temperatures. The CO_2 emissions cut would have to be realized at the same time as the world economy grows by 3.3% per year until 2050 and the global population grows to 9.2 billion in 2050 (IEA, 2008).