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Metal supply constraints for a low-carbon economy?

Arjan de Koning[a,*], René Kleijn[a], Gjalt Huppes[a], Benjamin Sprecher[a], Guus van Engelen[a,c], Arnold Tukker[a,b]

[a] *Institute of Environmental Sciences (CML), Leiden University, Leiden, Netherlands*
[b] *Netherlands Organisation for Applied Scientific Research TNO, Delft, Netherlands*
[c] *Currently employed at: Newpublic, Utrechtseweg 93, 3818 EC Amersfoort, Netherlands*

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ABSTRACT

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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* Corresponding author.
E-mail address: koning@cml.leidenuniv.nl (A. de Koning).

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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).

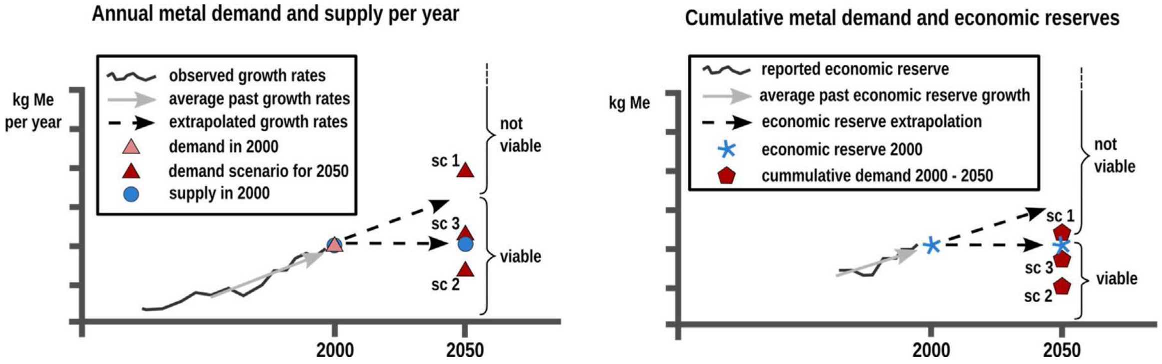

Fig. 1. Conceptual illustration of the viable operating space for metal demand in 2050 based on historical data. Scenarios requiring much higher growth rates of annual supply and demand than in the past (left) are outside the viable operating space. Scenarios requiring higher cumulative use until 2050 than economic reserves available in 2000 (right) are also outside the viable operating space. These two figures can be produced for each of the metals analyzed in this study. Please note that scenarios 1, 2, and 3 shown in the graphs are only examples and do not relate to the actual scenarios in the text.

4) **Rare Earth Metals (REM) scenario**, also on a 4° path. The REM scenario is similar to the BMES scenario but assumes additionally that all newly manufactured electric cars are equipped with neodymium magnets. Only the neodymium in the rare earth magnets is considered and not the dysprosium, which is currently an essential element in conventional rare earth magnets (Sprecher et al., 2014); the dysprosium content of rare earth magnets will likely decrease because neodymium magnets can be manufactured with 80% lower dysprosium content while retaining or even improving the favorable characteristics of conventional rare earth magnets (Chen et al., 2015). In the REM scenario the average electric car contains 690 g of neodymium, while in the TS and BMES scenarios the average electric car contains only 10 g of neodymium.

As can be seen from the scenario descriptions, these low-carbon futures require significant technological change in the electricity and (road) transportation sectors. We therefore calculated metal requirements for these sectors using detailed Life Cycle Inventory (LCI) data, combined with global annual capital goods production in these sectors, for instance for PV cells, wind energy, nuclear power plants, and electric cars (IEA, 2008; Keppler and Cometto, 2012; EPRI, 2004). Annual electricity production volumes and number of produced vehicles in each scenario are given in Tables A and C of the supporting information. Life Cycle Inventory data showing the amount of metals needed for the electricity production technologies (Da Silva et al., 2013; Van der Giesen, 2008; Laleman et al., 2013; Moss et al., 2011; Pihl et al., 2012; Wilburn, 2011) and amount of metals in the transportation vehicles (Burnham, 2012; Hawkins et al., 2012) are given in Tables B and D of the supporting information.

For activities *other* than electricity production and (road) transportation, we used EXIOBASE, a detailed global multi-regional environmentally extended Input-Output (IO) model (Tukker et al., 2013; Wood et al., 2014, 2015; de Koning et al., 2014, 2016). Onto this global IO model we imposed expected GDP growth from 2000 to 2050 (OECD, 2012b). We further assumed continuation of the trends in general efficiency improvement as observed from 1999 to 2009 using information from the World Input-Output Database (WIOD). The construction of the WIOD is described in Timmer (2012). Efficiency trends for all regions considered in our model were obtained by examining the amount of each input needed to produce a certain output by one of the 35 sectors available in the constant price series of the WIOD database. We assumed that the observed annual change (observed over a decade) in inputs required to achieve a certain output will continue until 2050. The final demand from these other sectors, in combination with the Leontief inverse of the 2050 table, resulted in an estimate of the primary demand for metals from these other sectors.

The IO scenario model[1] has previously been used to assess the effect of introducing renewable technologies on GHG emissions (de Koning et al., 2014, 2016). The scenario model covers the global economy, divided into four regions: the European Union, other developed countries, fast-developing countries, and the rest of the world. Each of these regions is on its own economic development path and connected by trade with the other regions. Each economic region is divided into 129 products/services and 129 industry sectors. The primary result of the scenario model is a set of supply-use tables that describe the structural global economic relationships. Converting the supply-use tables into an IO model gives us an estimate of the total demand for products in 2050 according to the four different scenarios, and therefore also an estimate of their total demand per metal in 2050.

The micro-level LCA information is combined with the information from the global IO model. The amount of metal used by specific climate change mitigation technologies is added to the rising demand for metals due to economic growth in general and the build-up of infrastructure in developing countries. A detailed description of the technologies used in the different scenarios and their associated metal use is given in the supporting information.

The scenario model that we have developed is different from previously published hybrid IO approaches in the field of energy technology scenarios. One such hybrid approach with a long history is the combination of MARKAL models with IO (Klaassen et al., 1999). An example of recent work is Daly et al. (2015), who estimated upstream CO_2 emissions across energy technologies for the UK. MARKAL-IO models typically focus on a single region and emissions of major air pollutants, not on the material requirements of energy technologies against a backdrop of global material requirements, like the scenario model used in this study. MARKAL models endogenously select the lowest cost energy technology, while the costs are uncertain and influence the outcome of the models (Bosetti et al., 2015). In the scenario model used in this study, energy technology scenarios are exogenously determined on the basis of technical and socio-economic considerations, and both their GHG emissions and material use are taken into account, integrated in a global multi-regional IO model.

Another class of hybrid IO models is integrated LCA-IO models. Typically these models are used to investigate the environmental and economic impacts of introducing a specific (new) technology in a particular country. For instance, the influence of using alternative fuel options for public transportation (Ercan and Tatari, 2015) or the introduction of a sugarcane-based biofuel industry in Australia (Malik et al., 2014). In these studies the new technology is combined with an IO model that describes a static economic background. The scenario model in this study uses LCA data to change a wide range of sectors,

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[1] Octave source code implementing the scenarios, all starting data and resulting supply-use tables are freely downloadable from: https://www.universiteitleiden.nl/en/research/research-projects/science/cml-cecilia2050-optimal-eu-climate-policy.

from electricity production, transportation, and cement to households. The IO model does not act as a static background but is changed to reflect the structure of the economy in 2050 as it develops according to different scenarios.

Two types of models that do indeed overlap with the scenario model used in this research are macro-econometric models and computable equilibrium models (CGE). However, these models do not have the sectors/product resolution and the GHG and material information required to enable an assessment as carried out in this study.

A limitation of our combined LCA-IO scenario model is the absence of built-in economic mechanisms and lack of price information, which are central elements in macro-econometric and CGE models. Structural changes in the economy, such as shifts from primary sectors to service sectors or shifts in trade patterns, have to be added exogenously in the IO scenario model. A further limitation of our combined LCA-IO scenario model is its lack of a recycling sector that allows for the estimation of metal recycling flows. This means that our scenario model structurally overestimates annual primary demand for metals in 2050.

3. Results

The 2050 demand per metal and per scenario is calculated with the combined LCA-IO model, as a ratio to the annual metal demand and supply in 2000, see Fig. 2. As indicated, in all scenarios we used a global real GDP growth (in constant prices) based on OECD (2012) of 2.4% per year, leading to a factor 3.2 higher GDP in 2050 compared with 2000. The results in Fig. 2 show a general growth in metal demand by a factor of 3–4, and hence imply a slight overall increase in the metal intensity of the economy.

The actual metals demand in 2000 and the estimates for metals demand in 2050 form the basis for an estimate of the cumulative amount of metals consumed from 2000 until 2050. We use the simplest assumption on annual rise of consumption of metals from 2000 until 2050: a linear increase in demand for metals. The linear trend assumption gives a higher total use over this period than a compound growth rate because the compound growth rate is convex to the linear trend. The resulting estimate for cumulative metal demand is compared with the known economic reserves in 2000 (Kelly and Matos, 2009). Cumulative metal demand until 2050 for the four scenarios divided by the known economic reserves in 2000 is shown in Fig. 3.

The values presented in Figs. 2 and 3 can be recalculated to produce a compound rate by which the annual production rate or economic reserve expansion of metals would have to increase. Table 1 does so for the required growth in metal production, compared with two historical ranges of production changes; using two different time periods gives some additional insight into the possibilities for adjusting supply to demand. Table 2 does so for the required expansion of reserves, compared with the actual expansion of reserves in the past.

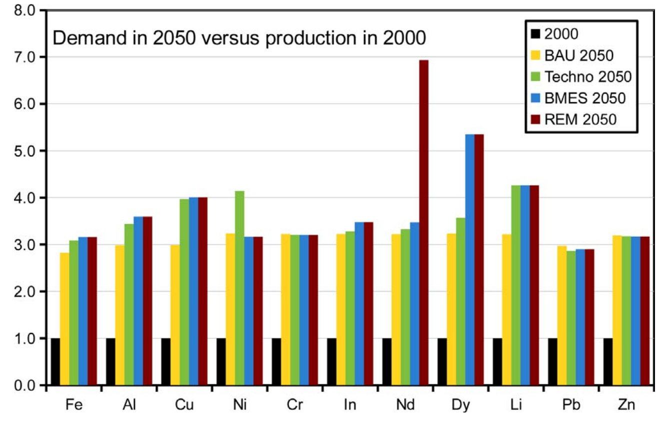

Fig. 2. Annual supply of metals in 2000 versus demand for metals in 2050 in the BAU, Techno, BMES and REM scenarios in 2050. Indexed values; annual supply of the metal in 2000 = 1.

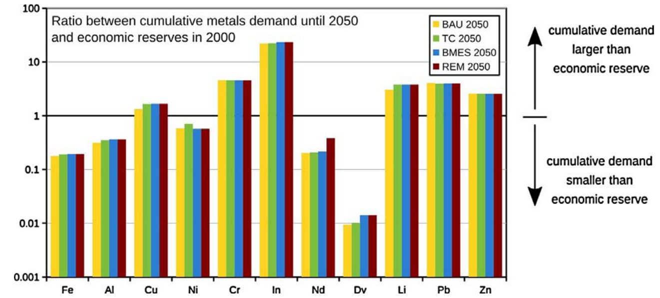

Fig. 3. The ratio between cumulative metals demand from 2000 until 2050 and the known economic reserves in 2000. Economic reserves in 2000 are set at '1'. The y-axis has a logarithmic scale.

Table 1
The annual metal production growth rate required to satisfy demand for metals in 2050.

Category	Scenarios of annual growth rate of production (%)				Observed annual growth rate of mining production (%)	
	BAU 2050	TS 2050	BMES 2050	REM 2050	1980–2006	1992–2006
Fe	2.1	2.3	2.3	2.3	2.8[a]	5.0[a]
Al	2.2	2.5	2.6	2.6	3.1	4
Cu	2.2	2.8	2.8	2.8	4.5	8
Ni	2.4	2.9	2.3	2.3	2.7	3.2
Cr	2.4	2.4	2.4	2.4	2.3	3.8
In	2.4	2.4	2.5	2.5	10	10.8
Nd	2.4	2.4	2.5	4	6.4[b]	7.5[b]
Dy	2.4	2.6	3.4	3.4	6.4[b]	7.5[b]
Li	2.4	2.9	2.9	2.9	5.7	6.9
Pb	2.2	2.1	2.2	2.2	0.1	0.8
Zn	2.3	2.3	2.3	2.3	2.1	2.5

Note: See supporting information for a plot of reported mining production (Figure A).

[a] Fe ore mining production data.

[b] Rare earths mining production data.

Table 2
The annual expansion rate required to satisfy cumulative metal demand until 2050.

Category	Annual rate of economic reserve expansion (%)				Observed historical rate of economic reserve expansion (%)
	BAU 2050	TS 2050	BMES 2050	REM 2050	1992–2006
Fe	s.	s.	s.	s.	1.4
Al	s.	s.	s.	s.	0.6
Cu	0.6	1	1	1	3
Ni	s.	s.	s.	s.	2
Cr	3.1	3.1	3.1	3.1	−3.8
In	6.4	6.4	6.5	6.5	n.a.
Nd	s.	s.	s.	s.	n.a.
Dy	s.	s.	s.	s.	n.a.
Li	2.3	2.7	2.7	2.7	4.6
Pb	2.9	2.8	2.8	2.8	0.4
Zn	1.9	1.9	1.9	1.9	3.3

Note: s. means sufficient because the economic reserves in 2000 are already large enough to satisfy cumulative demand until 2050. No historical data could be found on the development of economic reserves of the metals In, Nd, and Dy. See supporting information for a plot of reported economic reserves (Figure B).

4. Discussion

The BAU scenario requires a growth in production of the researched metals of 2.1–2.4% per year, which in all cases, except for lead, is less than the historical supply growth between 1980 or 1992 and 2006. This is partly because future global economic growth is estimated at 2.4% (OECD, 2012b), considerably lower than over the last 25 years. For most metals we see a BAU demand growth in line with economic growth, and very little decoupling of material use from economic growth. This runs counter to policy intentions of, for instance, large economic blocks like the EU, whose ambition is to put strong resource-efficiency policies in place (EC, 2014). For major metals such as Fe, Al, and Cu, the BAU scenario shows a slight decoupling, due to the fact that our model is based on the assumption that the efficiency gains shown by economic sectors in the past can be extrapolated into the future (see Methods section).

As expected, metal demand is higher in the various low-carbon scenarios. However, apart from some exceptions, this additional demand is quite small. In the Techno scenario, the introduction of low-carbon technologies leads to a demand growth in aluminum, copper, indium, neodymium, dysprosium, and lithium slightly above the base level of economic growth (2.4% per year, or a factor of 3.2). The largest demand growth is for lithium, with a factor 4.3 increase in 50 years, or 2.9% per year. Changing the electricity supply mix in the direction of more renewables, as in the BMES scenario, increases the demand for metals compared with the BAU scenario, but not by very much. In the BMES scenario, dysprosium demand becomes larger by a factor of 5.3 than the demand in 2000, while in the BAU scenario this is a factor of 3.2. The REM scenario shows that full electrification of private cars in 2050, using solely neodymium magnet based technology (about 690 g of Nd per car), raises Nd demand by a factor of 6.9 compared with 2000 (Fig. 2), while in the BAU scenario this is a factor of 3.2. The REM scenario would require a 4% annual supply growth of Nd.

The annual increase in metals demand is to a large extent determined by the use of these metals in many applications in an expanding global economy, rather than their specific use in renewable energy technologies, electric cars, and construction (Table E and Table F in the supporting information). It is only for copper, lithium, and indium in general, and neodymium in the REM scenario, that demand is raised substantially above the expansion rate of the global economy by the change in electricity generation technology and the massive introduction of electric cars. An example is the specific use of lithium in car batteries. While its use in car batteries increases 2.0×10^3 times, the overall demand growth for lithium is only a modest factor of 4.3 (2.4% p.a.). This is because lithium is now primarily used in ceramics, glass, other types of batteries, and greases, rather than for electric car batteries (DOE, 2010).

Looking at the annual expansion of metal production required for the BMES scenario, the largest annual increase is found for dysprosium at 3.4% per year. In the REM scenario, the largest annual increase is found for neodymium at 4.0% per year.

Fig. 3 shows that the high estimate of cumulative demand for iron, aluminum, nickel, dysprosium, and neodymium until 2050 can be met by the currently known economic reserves of metals. However, this does not mean that no further development of mines is necessary. Particularly the production rate of dysprosium and neodymium has to be increased. But as Table 1 shows, historical data on the growth rate of mining production indicates that this is well within the range of normal technical capabilities. In the period 1980–2006, the mining production of the metals under consideration showed a minimum of 2% annual increase, often exceeding 4% per year. The only exception is mining production of lead, which saw increases of well below 1%, probably because the use of lead was restricted in various applications due to toxicity concerns (Tukker et al., 2006). We refer further to Table 1 and the supporting information.

For copper, chromium, indium, lithium, zinc, and lead, the current economic reserves as known in 2000 are not sufficient to meet the cumulative demand for these metals until 2050. Additional mines of similar quality have to be developed, metal prices have to increase, or improvements in mining and refining technology have to be made in order to expand the economic reserves and satisfy cumulative demand. These economic reserves would have to increase by a factor of 1.6 for copper and 23 for indium by 2050, barring substitution.

This annual expansion rate of the economic reserves of copper, chromium, and lithium is modest: between 1.0% and 3.1%. As shown in the supporting information, such expansions of economic reserves have been achieved in the past decades (from 1992 to 2006), in a period of declining metal prices. Only for indium is a higher expansion of economic reserves of close to 7% per year required. Indium is a special case, however. It is only produced as a by-product of zinc refining. Very few zinc refineries extract indium in their process at present, whereas they might do so if the price of indium were to increase, leading to a much higher supply of indium (USGS, 2012; Polinares, 2012). Elshkaki and Graedel (2013) also identify indium as problematic. These authors state that while indium reserves are more than sufficient to meet demand until 2050, the problem lies in increasing the supply rate; however, they do not make the connection with zinc refining.

The high growth rate of neodymium in the REM scenario may be a bottleneck. In that scenario, all electric cars are going to use neodymium magnets, causing demand for that metal to surge to levels that require annual expansion rates far above 3%. But alternative technologies are available for that specific case, such as non-permanent electric magnets based on copper, as now already used in Tesla cars and some wind turbines. The answer to this problem is therefore simple: if neodymium supply problems occur, the BMES scenario may become reality, with private electric cars using non-permanent magnets based on copper. It should further be noted that a 4% supply expansion of neodymium is still well within the historically realized supply expansion of 6–7% per year up to 2006 (see Table 1).

5. Conclusions

Our work confirms the significant rise in metal requirements for a low-carbon transition in the (land) transportation and electricity sectors that has been reported by others (e.g. Kleijn et al., 2011; Gruber et al., 2011; Alonso et al., 2012; Roelich et al., 2014). Yet we also show that, because existing uses of metals in other sectors in society will not require a drastic transition, the overall annual supply increase needed to satisfy future metal demands in low-carbon scenarios is not extreme. Indeed, the various scenarios, including those with strong low-carbon ambitions such as the BMES and REM, require a modest supply growth compared with recent historical data on the realized growth in metal supply. This is in line with the conclusions of Elshkaki and Graedel (2013) and a detailed LCA study of Hertwich et al. (2015) on low-carbon technologies. They concluded that while copper and iron requirements of the power system would rise significantly, “only two years of current global copper and one year of iron production will suffice to build a low-carbon energy system capable of supplying the world’s electricity needs in 2050”. Because our method does not take account of recycling as a metal supply source, it might even overestimate the demand for primary metals. Iron is such a case. According Pauliuk et al. (2013), demand for primary steel peaks between 2020 and 2030, and increasing secondary production will satisfy a still increasing total steel demand.

In the context of our framework of a viable operating space, we see that the BAU and TS scenarios require less supply growth than the BMES and REM scenarios, but apart from Nd and Dy the differences are relatively small. We see that for all scenarios the required supply expansions fall well within the historical supply growth rates. From the perspective of required growth of economic reserves, the 7% annual expansion of indium stands out, but this problem is similar in all scenarios and can probably be solved by increasing by-production from Zinc mines. At this point we would therefore conclude that all the scenarios in principle face similar challenges in metal supply in the future, rather than some being more viable and others less so, given our viable operating space framework. These conclusions are obviously limited to Fe, Al, Cu, Ni, Cr, In, Nd, Dy, Li, Zn, and Pb, the metals we researched. The situation could be different for other metals (e.g. silver, tellurium, and germanium for specific PV technologies, as suggested by Elshkaki and Graedel (2013)).

There are reasons not to be complacent, however. The analysis shows that production of virtually all metals relevant for the low-carbon transition will have to increase significantly. Since it may take a decade or more to open mines, especially large, deep open-cast mines, investments in new mining operations have to take place well in advance of increases in production. At present, however, it is politically uncertain whether a low-carbon society will develop and, if so, which scenario will materialize. This makes the return on investment uncertain and investors may not invest in new mines in time. Demand-supply imbalances and price hikes may then occur, particularly if government policies are unexpectedly and widely adopted, causing a much faster transition to low-carbon technologies and electric vehicles than the 100% implementation by 2050 that we assumed in our BMES and REM scenarios. Building new mines and expanding existing ones has negative local environmental consequences, which can also be a delay factor, especially if these reserves are located in fragile environments. Moreover, in the case of several metals it is necessary to exploit new deposits, which may have lower metal ore concentrations than are currently available. Extracting metals from ore bodies with lower metal concentrations means that more energy, water, and auxiliary materials are needed to extract the metal, with possibly higher environmental impacts and larger political risks (Prior et al., 2012).

The main message of this research is that availability of Fe, Al, Cu, Ni, Cr, In, Nd, Dy, Li, Zn, and Pb is unlikely to be a bottleneck for the transition to a low-carbon energy system. However, the combination of lack of certainty about return on investment, long lead times in expanding mining production, and concerns about impacts of mining that delay expansion of mining capacity may well create imbalances in demand and supply (Tukker, 2014; Sprecher et al., 2015).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2017.10.040.

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