Environmental Implications of Future Demand Scenarios for Metals

Methodology and Application to the Case of Seven Major Metals

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Summary

In this paper, we develop a method to assess the environmental impacts of metal scenarios. The method is life cycle based, but enables forward looking and upscaling. The method aims at translating metal demand scenarios into technology-specific supply scenarios, necessary to make the translation into environmental impacts. To illustrate the different steps of the methodology, we apply it to the case of seven major metals. Demand scenarios for seven major metals are taken from literature. We translate those into technology-specific supply scenarios, and future time series of environmental impacts are specified including recycling rates, energy system transformation, efficiency improvement, and ore grade decline. We show that the method is applicable and may lead to relevant and, despite many uncertainties, fairly robust results. The projections show that the environmental impacts related to metal production are expected to increase steeply. Iron is responsible for the majority of impacts and emissions are relatively unaffected by changes in the production and energy system. For the other metals, the energy transition may have substantial benefits. By far, the most effective option for all metals appears to be to increase the share of secondary production. This would reduce emissions, but is expected to become effective only in the second half of the twenty-first century. The circular economy agenda for metals is therefore a long-term agenda, similar to climate change: Action must be taken soon while benefits will become apparent only at the long term.

Introduction

Scenario analysis is a powerful tool to envisage possible future developments that can be used to support forward-looking strategies and policies. Scenarios can be used at any scale level and for many purposes. Well-known scenario studies at the global level are the energy and climate scenarios of the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) (e.g., IEA 2012; IPCC 2014). These contain projections of developments in the global energy and climate systems under different assumptions of demographic and socioeconomic development and of energy and

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climate policies. They show us the consequences of not addressing the issues and also show the potential effectiveness of what could be done to address them. These scenarios are constructed in a number of steps, combining knowledge of different fields in one comprehensive effort. They contain demographic, economic, technological, and environmental information, all needed to make sensible forecasts. Generally, it is stressed that such scenarios are not predictions. They are representations of storylines telling us in what directions the future could unfold, rather than aiming at being accurate in what actually will happen. By showing consequences of certain potential developments and options to mitigate, they provide a powerful basis for international and national policies and have a large influence on corporate policies as well.

Climate change is perceived to be one of the major global challenges of the twenty-first century. Another such major challenge is providing the growing world population with sufficient resources (UNEP 2011). Present trends in global resource extractions are steeply upward, with no sign of slowing down, leading to worries about the sustainability of resource supply in the future. While for energy and climate change, scenarios are used to explore potential futures, this is not yet the case for global resource extraction and use. No generally accepted global-level quantitative resource scenarios exist at this moment. This can be considered a huge gap in addressing the resource challenge. Presently, policies tend to focus on immediate problems related to criticality—the availability of sufficient raw materials over the next few years for national economies and for industries to continue being profitable (e.g., Mancini et al. 2013; Teske et al. 2016; Tisserant and Pauliuk 2016). A long-term interest in resource-related issues is slowly growing, as is the insight in the developments and dynamics around resource supply, especially related to metals. Some attempts have been made to link resource extraction to energy and greenhouse gas (GHG) emissions (Moya et al. 2015; Paraskevas et al. 2016a, b; Luo and Soria 2008; Cheah et al. 2009; Chen and Shi 2012; Pauliuk and Müller 2014; Yellishetti et al. 2010) or have linked metal demand to changes in the energy system (Stamp et al. 2014; Dawkins et al. 2012; Elshkaki and Graedel 2013; Kleijn et al. 2011; Liu et al. 2011; UNEP 2016). A comprehensive environmental assessment is not available.

This gap is now being addressed by the United Nations (UN) International Resource Panel (IRP). The IRP has initiated a scenario activity to develop forecasts for metals, biomass and construction minerals, and estimate future demand for these resources up to the year 2050. In that framework, a first attempt at defining demand scenarios has been made by Elshkaki and colleagues (2016a, b). These scenarios are based on the GEO-4 scenarios developed by the UN (UNEP 2007). They do not contain any specific resource policies as they were drafted with climate and energy developments in mind. From the point of view of resources, therefore they have to be regarded as variants of business-as-usual scenarios. Forecasts of resource use have been made using the socioeconomic specifications of these GEO-4 scenarios. For metals and construction minerals, the demand is expected to more than double or even triple until 2050 (Elshkaki et al. 2016a, b).

The development of scenarios addressing the demand for materials is only one part of the storyline. The other part is the consequences of such a demand rise. Can future demand be met by supply? Where can we expect bottlenecks? Which elements will become critical? And what about the sustainability of future resource supply?

This paper contributes to specifying such consequences. The focus is on the environmental consequences of an increasing metal demand. Metals are energy-intensive materials (UNEP 2013). Will energy use increase with the same rate as demand? Will environmental impacts follow? Will there be implications for climate policies? Are there runaway effects or feedback loops? Can we imagine scenarios where impacts will not increase with demand, and how could these be constructed?

The answer to these questions very much depends on how this demand is actually supplied. We cannot simply assume that the present supply technology mix will be constant over a period of decades, and we do know that different production routes have widely different environmental impacts. That means we have to define matching supply scenarios to the demand scenarios. Influential supply-related variables are, among others: the share of secondary production, developments in efficiency, innovations in production, changes in the background system, developments in ore grades, and substitution of metals by other materials. Some of these variables will contribute to reducing environmental pressure, others may increase it. It is not possible to estimate without further analysis how the environmental impacts related to metal use will develop.

In this paper, we present a methodology to quantify environmental impacts related to future metal demand, including several of the above-mentioned issues. The method falls within the framework of life cycle sustainability analysis (LCSA). LCSA is a new and potentially very relevant research field originating from the field of life cycle assessment (LCA). A generally accepted definition of LCSA is not yet available, but presently there is a small body of studies claiming to be LSCA studies. An up-to-date overview of the literature is provided by Guinée (2016). This publication also contains a discussion on LCSA definitions. LCSA is perceived as a framework and not as a specific method (Guinée and Heijungs 2011). The idea of cradle-to-grave chains is maintained, but applied in a broader way than just to assess environmental impacts related to micro-level product or service systems. The whole development stems from the need for a life cycle approach to apply to other, broader types of questions than can be answered with the classic LCA.

Important aspects in the transformation of LCA into LCSA are the following (Guinée et al. 2011; Guinée 2016):

- Broadening the scope by including social and economic impacts: adding life cycle costing and social LCA to the environmental LCA to cover the three pillars of sustainability in one framework
- Broadening the spatial scale by applying life cycle thinking to larger systems, such as sectors or national

economies, that may change society's metabolism as a whole
- Broadening the temporal scale by forward-looking analysis: life cycle scenario analysis uses life cycle thinking in forecasting or backcasting scenario analysis to overcome the usually narrow focus and cover a broader array of relevant changes
- Deepening the analysis by including economic and behavioral relations within the system besides technical relations.

The methodology described in this paper specifically focuses on the second and third points: upscaling and forward looking. We will not address social or economic aspects explicitly. Instead, we will focus on the environmental dimension. The methodology is being applied to estimate future environmental impacts of demand scenarios of seven major metals: iron, aluminium, copper, zinc, lead, nickel, and manganese (Elshkaki et al. 2016b).

Methods and Data

The methodology presented in this paper aims, as mentioned, at upscaling and forward looking micro-level LCA information, while maintaining the life cycle perspective. Briefly summarized, the methodology contains the following steps to translate demand scenarios into technology-specific supply scenarios that can be used to assess environmental impacts:

1. Use existing LCA methods and databases to calculate present day cradle-to-gate environmental impacts of 1 kilogram (kg) of refined metal
2. Forward looking: specify and quantify developments in the environmental impacts per kg of metal over time, based on developments in supply generation, in time series until 2050
3. Upscaling: multiply the "adapted forward looking" per-kg impacts with the global-level production of the metal over time, again in time series until 2050.

Below, we explain the three steps in more detail.

Step 1. Use existing LCA methods and databases to calculate impacts per kg of metal

LCA is a method developed to calculate the environmental impacts related to cradle-to-grave product or service systems at the micro level. The LCA method is standardized under the International Organization for Standardization (ISO) (ISO 2006). It consists of three analytical steps: (1) goal and scope definition, (2) life cycle inventory (LCI), and (3) life cycle impact assessment (LCIA). A fourth step is called Interpretation, covering many aspects from commenting on uncertainties to providing context to the results of the first three steps.

To calculate the environmental impacts of metals, we made the following choices:

(1) The scope is the cradle-to-gate production system of 1 kg of refined metal.
(2) We used the ecoinvent v2.2 database for the LCI of the background system. For the foreground system, more specific process data can be collected and have been collected for several of the metals (Verboon 2016; Kuipers 2016).
(3) For the LCIA, we used the CML2002 impact categories (Guinée et al. 2002) as implemented in the CML-IA database (version 4.8). We added the cradle-to-gate energy requirement as an indicator as cumulative energy demand (CED), because of the importance of energy for the environmental impacts of metal production (UNEP 2013). A brief description of the LCIA method and the impact categories included can be found in Appendix 4 of the supporting information available on the Journal's website.

We used the CMLCA software (Heijungs 2012) to calculate the cradle-to-gate environmental impacts of the production of 1 kg of each metal, representative of the present situation. We made separate calculations for primary and secondary production, and sometimes included different primary production routes. In case of co-production, we used allocation based on the economic value of the outputs. For secondary production, we cut off at the point of waste generation. Collection, transportation, and smelting of scrap are therefore included in the secondary production inventory.

Step 2. Forward looking: changes in impacts per kg over time

The second step in the methodology is to identify and model changes in the production system, and derive time series of environmental impacts per kg of produced metal.

We identified the following variables as important for the environmental impacts, and likely to change over time:

- Changes in the demand for the metals
- The share of secondary production
- Ore grade developments
- Efficiency improvements in the foreground system
- Efficiency improvements in the background system.

The demand changes are not relevant for the changes in the impacts per kg, but belong to step 3, the upscaling. With regard to the other variables:

- Secondary production usually uses considerably less energy than primary production (UNEP 2013; Norgate and Rankin 2002; Gaballah and Kanari 2001; Rankin 2011), since mining and early processing steps are bypassed. Increasing the share of secondary production therefore can be expected to lead to a reduction of energy-related environmental impacts. We specify per-kg impacts for primary and secondary production separately. The share of secondary production of total metal supply in the different scenarios is part of step 3, the upscaling.
- Ore grades are important determinants for the energy required to produce metals from ores (Norgate and Haque 2010; Norgate and Jahanshani 2006; Norgate et al. 2007;

Norgate 2010). Ore grades of some of the metals have shown a downward trend over a longer period of time (Norgate 2010; Mudd et al. 2017; Northey et al. 2014). For these metals, it is likely that this will continue into the future. We used historical data from Mudd and colleagues (2017) to derive a trend as a mathematical equation for each metal, and assumed this trend to continue into the future. The ore grade decline is a complex issue, where various developments interplay (UN 2013). A brief discussion is included in Appendix 1 of the supporting information on the Web. Its relevance for the environmental impacts is derived from energy use: A relationship has been established between ore grade and energy use, indicating that production from lower-grade ores requires more energy (Valero et al. 2011).

- Efficiency improvements in the foreground system: Over time, metal production is becoming more efficient in various ways. Our focus has been on energy efficiency. Again, we used historical trend data of energy efficiency of production processes (World Aluminium 2016; World Steel Association 2016) and extrapolated those into the future. Details can be found in Appendix 2 in the supporting information on the Web.
- Efficiency improvements in the background system: The most important change is probably the change in the global energy system. The GEO-4 scenarios differ in their assumptions of the uptake of renewable energy technologies. In addition, these scenarios had to be translated into a technology-specific energy mix. We focused on the electricity mix, which is expected to change profoundly until 2050. The transport system also is expected to change, but fossil fuels still dominate in all of the scenarios. Other potential efficiency improvements in the background system have not been included.

For all of these variables, we constructed time series from 2010 until 2050 under two of the scenarios as specified by Elshkaki and colleagues (2016b). We used 5-year intervals, which means that, for each scenario and each production route of each metal, we have nine different environmental profiles per kg of produced metal, corresponding with the nine moments in time.

Step 3. Upscaling: calculating impacts of future global metal production

For the upscaling, the most important information we used are two of the global demand scenarios for metals as specified by Elshkaki and colleagues (2016b). These scenarios forecast global demand for 2010–2050. They specify the contribution of primary and secondary production to the supply over time. For two of the metals (copper and nickel), we additionally specified changes in the relative use of primary production routes at the global level. Thus, we have for each metal a time series of quantity of supply, distributed over the various production routes.

The final step is then to aggregate:

multiply the different quantities of supply with the respective impact levels per kg, for each production route, for the period 2010–2050, using again a 5-year interval
add it all up to time series of environmental impacts.

It is important to note that we did not take into account any novel technologies that might become available toward 2050. We do not have information on such technologies as they are not on the market yet, but they could influence the environmental impacts if they would be significant on the market. However, the process of upscaling novel technologies is a lengthy one. It cannot be expected that such technologies will represent a significant share of production as soon as 2050. On the longer term, they may become relevant.

Results

Variables Used to Calculate per-Kilogram Impacts of Metal Production

Primary and Secondary production

The GEO-4 scenarios of the UN have been adapted to include resource demand by Elshkaki and colleagues (2016a, b). The result of that adaptation are the following four scenarios:

- Markets First, a scenario where global developments are dominated by global markets
- Policy First, a scenario where policies are implemented to steer developments at the global level
- Security First, a scenario where globalization is no longer pursued and nation states tend to withdraw behind their own borders
- Equitability First, a scenario aiming at sustainable development, which includes a far-reaching transformation of the energy system as well as a marked improvement in global equity.

In our analysis, we limit ourselves to two of the four scenarios: Markets First and Equitability First. Markets First is a business-as-usual type of scenario, and the Equitability First scenario is interesting because of the assumed completeness of the energy transition, which may have a mitigating effect on environmental impacts of metal production.

The GEO-4 scenarios have their own projections of global population, gross domestic product (GDP) and welfare distribution, which are used by Elshkaki and colleagues (2016a, b) to estimate the future demand for resources. All scenarios have a substantial increase in demand, due to the expected developments in global population and welfare. The growth is least under the Security First scenario, as a result of reduced global trade and consequent hampered GDP growth. It is highest under the Equitability First assumptions, as a result of a more equal distribution of wealth throughout the planet.

The demand scenarios also include assumptions on the ratio primary/secondary production. Elshkaki and colleagues (2016b) took past trends in recycling rates and projected these into the future, not distinguishing between the different scenarios. In 2010, secondary production shares vary from less than 10% (zinc) to more than 50% (lead). In 2050, shares are generally higher, but the differences are still large: 13% (zinc) to 77% (lead). For most of the metals, changes in secondary production shares are minor, although the absolute amount of recycled material increases considerably.

Energy Mixes

The changes in energy mix differ per scenario, but obviously not per metal. However, the impact of a changing energy system may be different per metal, as the metals' energy intensities are quite diverging. The energy mixes for the two scenarios originate from the IEA World Environmental Outlook (WEO) energy scenarios (IEA 2012). We have assumed the Markets First scenario to correspond with the WEO Current Policy scenario, while we took the WEO 450 scenario to include in the Equitability First scenario.

The WEO scenarios include forecasts until 2035 only. We extrapolated the data linearly using a forecast function to provide time series until 2050.

In 2010, both scenarios have an electricity mix consisting of 67% fossil sources and 33% renewable energy sources. In the Current Policy scenario (applied to Markets First), this division stays the same. In the 450 scenario (applied to Equitability First), the fossil energy share is drastically reduced to 12%. In Appendix 3 in the supporting information on the Web, the electricity mixes for the different scenarios are shown.

These scenarios contain additional assumptions on the fuel mix. We did not use these, as the share of fossil fuels remains high in all scenarios and the fuel mix contributes little to the per-kg impacts of metals.

Ore Grades

For iron, aluminum, and manganese, we did not find evidence that ore grades are declining. The other four metals—copper, zinc, lead, and nickel—ore grades indeed show a long-term declining trend. Historical data as provided by Mudd and colleagues (2017), Crowson (2012), Mudd and Jowit (2013), Northey and colleagues (2014), and Mudd and colleagues (2013) have been used to derive mathematical descriptions of ore grade developments, that have been extrapolated into the future.

We have made estimations on future ore grades, based on a power regression of past ore grades. The power regression equation is shown in equation (1), where G is the ore grade in a specific year, t is time, and a and b are constants that determine the slope and position of the trendline.

$$G = a * t^b \tag{1}$$

The relation between ore grades and energy requirement has been addressed by several researchers. For zinc and lead, we used data from Valero and colleagues (2011). For nickel, the relation ore grade–energy requirement was taken from Norgate and Jahanshahi (2006). For copper, we used data from Northey and colleagues (2014).

In Appendix 1 in the supporting information on the Web, the equations of both ore grade developments and energy requirements are derived, and are shown for the relevant metals.

These two pieces of information—ore grade developments and the energy requirement (ore grade relation)—are used to derive multipliers for the metal production process. Our own assumption is that the processes related to extraction, crushing, and grinding are modified not just with regard to energy use, but also in their overall use of resources and emissions per kg of produced metal, since in fact larger amounts of ore must be processed to obtain this 1 kg.

Primary Production Routes and Efficiency Improvements

For nickel and copper, we specified different routes for primary production. The share of hydro- and pyrometallurgic production has been established, again based on historical data (Mudd 2010), and assumptions have been made on how this would develop over time (Kuipers 2016; Verboon 2016). For steel, we used the blast furnace and basic oxygen furnace route for primary production and the electric arc furnace route for secondary production, as this process uses scrap as its main input.

A complicating factor for the calculation of impacts related to the metals, iron, manganese, and nickel, is that significant amounts of these elements are used in different kinds of steel. Steelmaking is also a process that uses energy and is associated with environmental impacts. We have included two steelmaking processes: carbon steel (assumed to include Mn steel alloys) and stainless steel (where Ni is assumed to be applied). The impacts of steel production are attributed to the three elements, based on the mass of the flows actually going into the steelmaking process.

An important determinant for environmental impacts is the energy used in the production processes. Therefore, improvements in the energy efficiency of the production processes is also important. For several metals, historical data are available showing the energy requirements of primary production over time. We extrapolated past trends into the future to account for efficiency improvements. For steel, a clear trend is visible of improving process efficiency. We extrapolated that into the future, using an improvement percentage of 1.5% per year. For alumina production from bauxite, no trend of improvements is visible at the global level. For aluminum production from alumina, a slow improvement can be detected at the global level. Based on data of World Aluminium (2016), we assume a continuing trend of 0.5% improvement per year. The data for steel and aluminum efficiency improvement are shown in Appendix 2 in the supporting information on the Web.

Environmental Impacts per Kilogram

The above-mentioned variables are translated into environmental impacts per kg of produced metal according to step 1 in the methodology. Figure 1 shows cradle-to-gate environmental impacts per kg of metal for the present situation, calculated with the CMLCA software, for two impact categories: CED and global warming.

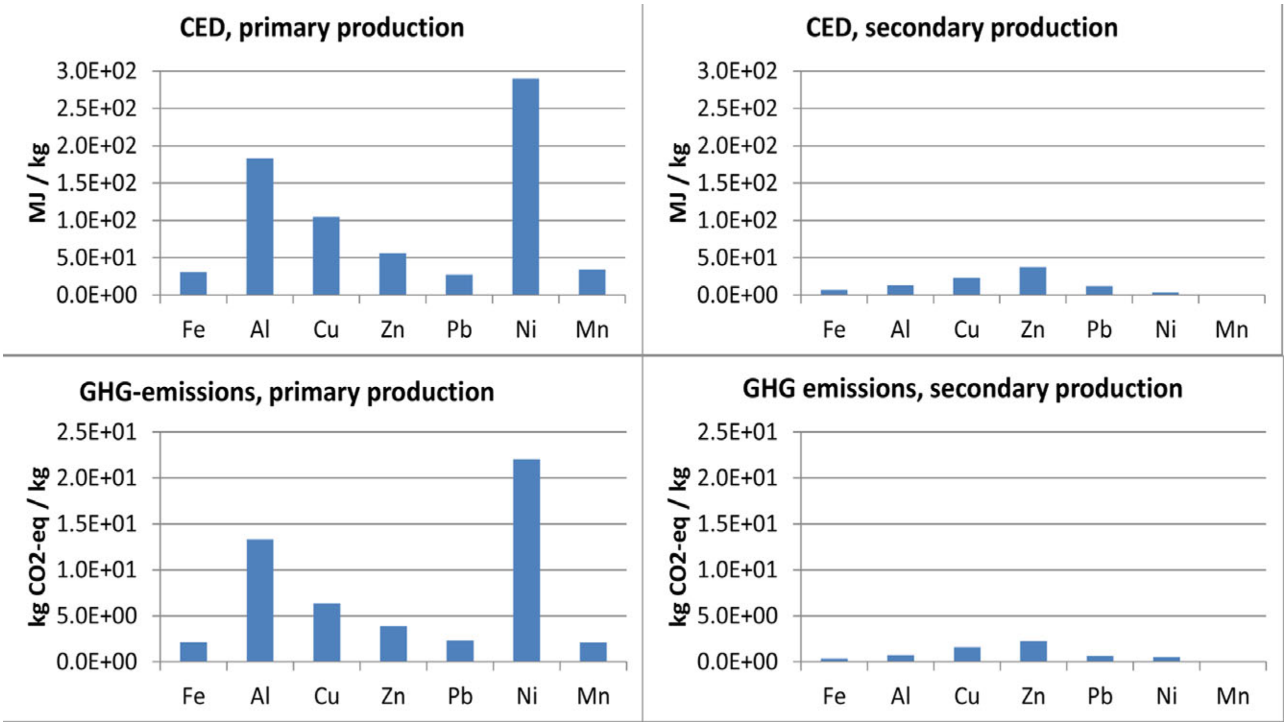

Figure 1 Cumulative energy demand (CED) and greenhouse gas (GHG) emissions per kg of produced metal, 2010 (numbers for iron, nickel, and manganese include steelmaking). MJ/kg = megajoules per kilogram; kg CO2-eq/kg = kilograms of carbon dioxide equivalent per kilogram.

As can be seen from figure 1, differences between metals are considerable. Aluminum and nickel are relatively energy intensive and therefore have high GHG emissions. For all metals, though, secondary production has considerably lower scores than primary production.

These per-kg impacts will change over time, according to the variables discussed above. In figure 2, we show and discuss some results of step 2 of the methodology, specifying time series of environmental impacts.

In figure 2, we see the influence of declining ore grades on the CED in both scenarios for copper, nickel, and lead. Energy efficiency gains show clearly for aluminum. The difference in CED/kg metal between the Markets First and Equitability First scenarios are small, but the differences in GHG emissions/kg are considerable and again show most markedly for aluminum and manganese. In the Equitability First scenario, the advanced energy transformation shows clear benefits for the more electricity-intensive metals. For iron, there is not much change in any of the scenarios.

Changes in the per-kg impacts appear to be gradual. The only variabe that seems to have a considerable influence on several of the impact categories for several metals, is the transition towards a renewable energy system. Drastic innovations in production processes are, however, not included in the scenarios.

A complete overview of per-kg impacts under the different scenarios can be found in Appendix 4 in the supporting information on the Web.

Environmental Impacts of Global Scenarios

The third step in the methodology is to upscale: multiply time series of metal supply with the time series on impacts per kg, to obtain a picture of the global level environmental impacts related to metal production. Figure 3 shows the GHG emissions related to production of the seven metals under the two scenarios.

Figure 3 shows that GHG emissions rise together with production. The Equitability First scenario with the highest demand growth also has the highest level of emissions. It appears that the considerable improvements in the per-kg impacts under the Equitability First scenario are more than offset by the demand increase.

Despite the relatively low per-kg impact of iron, the sheer production size compared to all other metals makes iron dominant even in GHG emissions. Due to the fact that the transition toward a renewable electricity system has relatively little benefits for iron, the demand growth trend is only slightly mitigated by the reduced emissions per kg. For the other metals, the increase in GHG emissions is considerably less than the increase in demand.

In relative terms, we see the following trends, depicted in figure 4.

In figure 4, the Markets First scenario shows an increase in GHG emissions for all metals that conforms more or less to production increase. In the Equitability First scenario, the steepest rising trend in GHG emissions is for iron, which metal

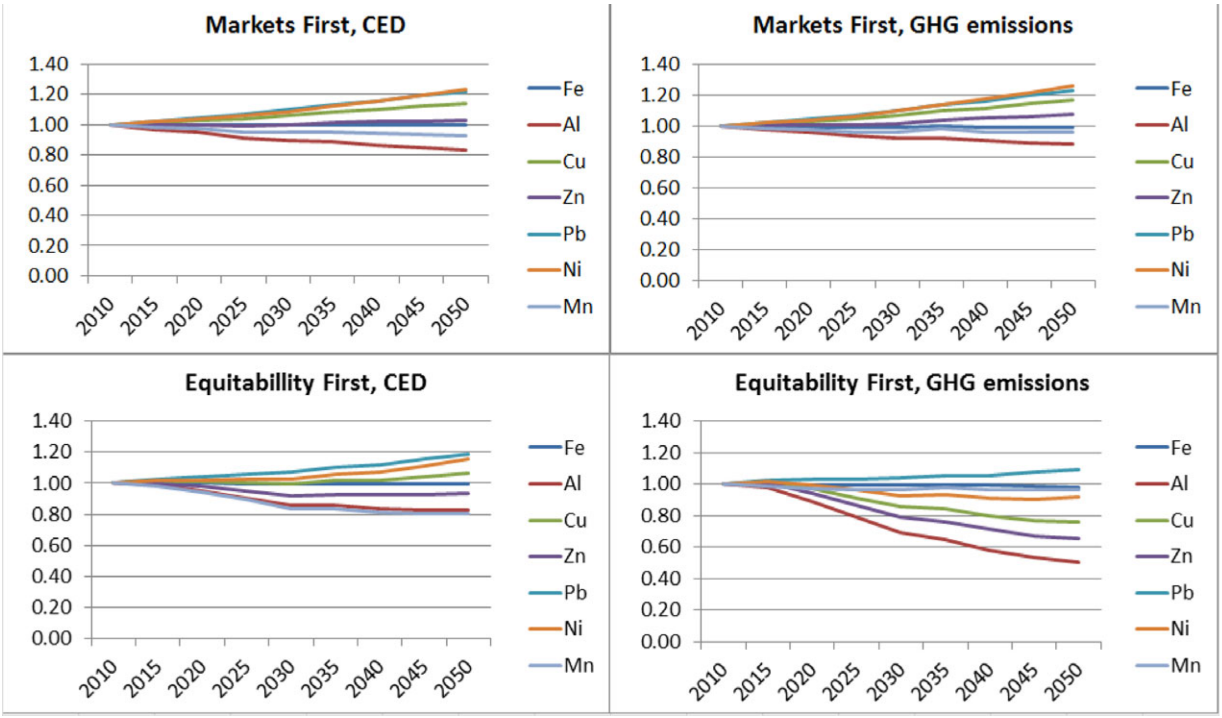

Figure 2 Relative changes over time in per kg of cumulative energy demand (CED) and greenhouse gas (GHG) emissions of primary produced metals (2010 = 1).

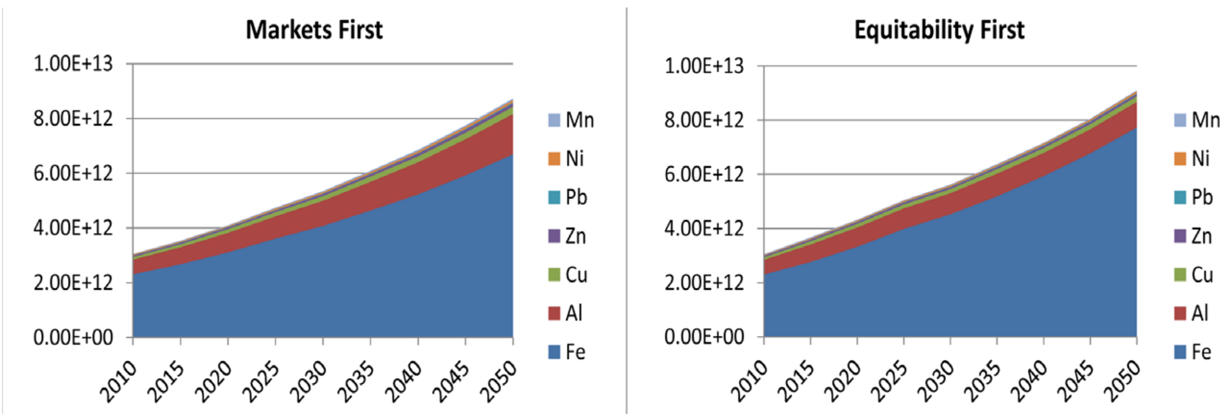

Figure 3 Greenhouse gas emissions related to the production of seven metals under Markets First and Equitability First scenarios, 2010–2050 (kg CO_2-equivalent per year). kg CO_2 = kilograms of carbon dioxide.

is relatively unaffected by the renewable electricity system. For aluminum and manganese, the energy transition in the Equitability First scenario has a profound effect: Emissions rise by only a factor of 1.2 to 1.5 while the demand triples under this scenario. Still, the powerful growth of demand is not offset completely by the improved environmental performance even for these metals.

For the other impact categories, shown in figure 5, the conclusions are rather similar as far as the upward trend of the impacts are concerned. Iron is dominant for fossil-fuel–related impacts (CED, acidification, and photochemical smog formation) and for land use, but not for toxicity and for abiotic nonfossil resource depletion. In those areas, copper has the largest contribution, now as well as in the future under these scenarios. These two impact categories are also relatively unaffected by the energy transition. A complete overview is provided in Appendix 5 in the supporting information on the Web.

As can be seen from figure 5, demand grows with a factor of 2.5 to 3.0 in the Markets First scenario for all metals, while impact categories, by and large, show the same increase for all metals. In the Equitability First scenario, demand grows even more: a factor of 3.0 to 3.5. In general, we see that abiotic resource depletion grows faster than demand in the Equitability First scenario. This is partly due to the fact that renewable energy technologies use more materials, especially metals, than fossil energy technologies—a phenomenon that is mentioned

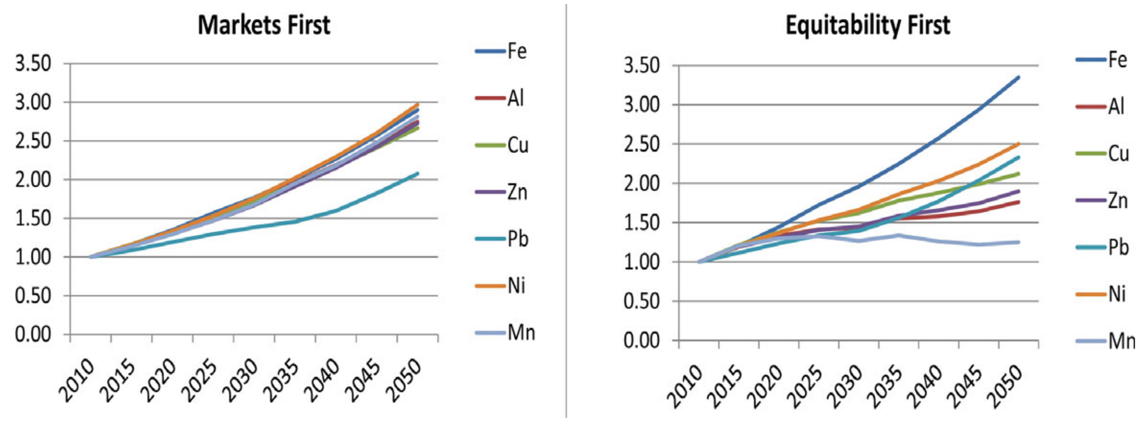

Figure 4 Relative development of greenhouse gas emissions related to the production of seven major metals under the Markets First and Equitability First scenario, 2010–2050 (2010 = 1).

in the scientific literature as well (Kleijn et al. 2011; UNEP 2016). Other impact categories grow as well, in the Markets First scenario with demand, and in the Equitability First scenario slightly less than demand. In the Equitability First scenario, impact categories show a more varying behavior, that is different for each metal.

Below, we discuss important trends for iron and aluminum, the two metals that contribute most to environmental impacts. For the other metals, a similar description is provided in Appendix 6 in the supporting information on the Web.

Iron

Iron shows little change in per-kg impacts for both scenarios, as is presented in figure 6. For the Markets First scenario, emissions related to iron production rise with demand. For the Equitability First scenario, a slight decrease in the rising trend can be observed for most of the impact categories: Impacts increase less than demand. However, due to the steel demand growth in the Equitability First scenario, the impacts are still higher than those of the Markets First scenario. The transition to the renewable energy system has remarkably little effect on the iron production system. Most of the fossil-fuel use is related to cokes, a process material that is not affected by the energy transition. Significantly reducing emissions is therefore not possible without a completely novel low-carbon production process, or without significantly increasing the share of secondary production. As iron is the dominant metal in terms of size and impacts, this fact is important for the performance of the whole group of metals.

Aluminum

For aluminum, main emissions come from the use of electricity. The energy transition of the Equitability First scenarios therefore has a powerful effect on reducing emissions, as can be seen in figure 6. GHG emissions are considerably reduced compared to the Markets First scenario, and are also reduced compared to energy use. This transition also seems to have a powerful effect on resource depletion, growing very rapidly. A contribution analysis shows that this is related to the energy system and does not refer to aluminum itself, but to minor metals assumed to be applied in energy technologies. It is important to note that these are relative changes. Even with a factor 8 growth, the contribution of aluminum to resource depletion is still minor. Apart from resource depletion, all impact categories develop below the demand line.

A Circular Economy Scenario

Looking at the influence of the five different variables—demand growth, share of secondary production, energy transformation, ore grade development, and energy-efficiency increase—we can conclude that the increase in demand is dominant. The influence of the other variables differs per metal. The renewable electricity system has a profound influence on per-kg impacts of metals like aluminum, that use much electricity in their production process, but hardly influences the per-kg impacts of iron. Process efficiency improvement in theory could be beneficial, but in practice it seems to be a slow process, not leading to a substantial emission reduction over the period of investigation. These variables together are not sufficient to reach an absolute decoupling between metals use and environmental impacts. In addition, ore grade developments decrease the process efficiencies of copper, lead, zinc, and nickel, and even lead to an overall increase in per-kg impacts for lead where the other variables are relatively unimportant.

There is one variable, however, that has not shown its potential yet in these scenarios. Secondary production in all cases uses much less energy than primary production (figure 1), and could result in the most powerful change of all. In the case of lead, the only metal with a high share of secondary production, we clearly see its reducing influence on the impact categories. However, secondary production is not expected to have a large share in the supply over the 2010–2050 period for the scenarios included in this paper, due to the huge demand increase over that period. Metals usually have a long life span, which implies that in a situation of growing demand a

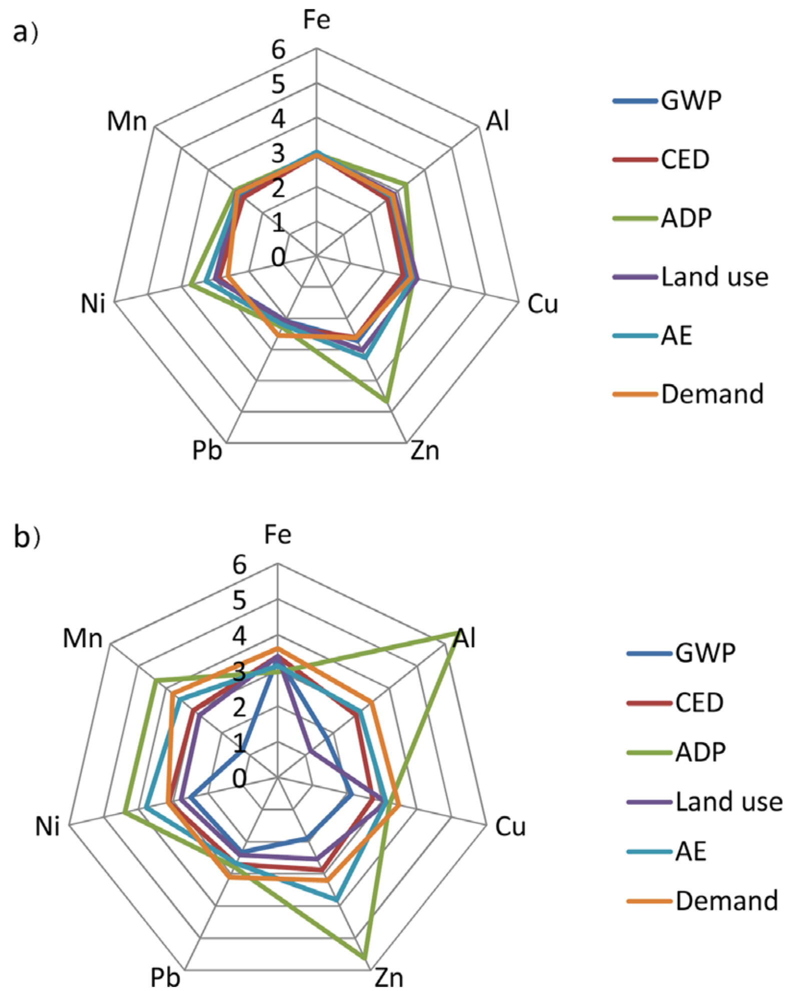

Figure 5 Relative development of impact categories 2010–2050 under two scenarios for seven major metals (2010 = 1) (a: Markets First scenario; b: Equitability First scenario). ADP = abiotic depletion potential; AE = aquatic ecotoxicity (freshwater); CED = cumulative energy demand; GWP = global warming potential.

recycling rate of even 100% still results in a modest share of secondary production: The amount available for recycling corresponds to the demand of many years ago, not to the present demand.

In order to test the potential effectiveness of a larger share of recycling, we defined a Circular Economy scenario and applied that to iron and aluminum, the two metals contributing most to the impacts. This scenario is based on the Equitability First scenario, the scenario with the highest welfare growth and distribution as well as with the most advanced energy transition, and the scenario that shows the highest increase in demand. We expanded this scenario until 2100 to allow for sufficient time for secondary production to increase substantially also in a relative sense. We assumed an average life span of applications of 30 years and a recycling rate of 90%. We assumed demand to increase as before until 2080, and after that we assumed it to increase at a slightly lesser rate, as a result of the stabilization of the global population that is expected to occur. These assumptions are not realistic in the sense that many barriers, of both societal and technological nature, need to be removed in order to reach such figures. Nevertheless, we make them, to show the potential of this direction of development.

Figure 7 shows the demand, and the shares of primary and secondary supply, for iron and aluminum.

Figure 7 shows that, despite the still steeply rising demand, the share of secondary production can go up considerably if indeed a 90% recycling is established by 2040, and kept up until 2100. As a result, the share of primary production can be reduced and may even be reduced in an absolute sense, after reaching a peak at around 2085 for iron and 2070 for aluminum.

What does that imply for GHG emissions? Under the Equitability First scenario, GHG emissions per kg of metal are reduced as a result of the energy transition. For iron, the decrease is only slight, for aluminum it is considerable. We have assumed the downgoing trend to continue until 2100, as a result of the completion of the energy transition. If combined with the supply projections of figure 7, the resulting GHG emissions would develop as shown in figure 8.

Figure 8 shows that under the circularity scenario, GHG emissions will eventually be reduced not only for aluminum with

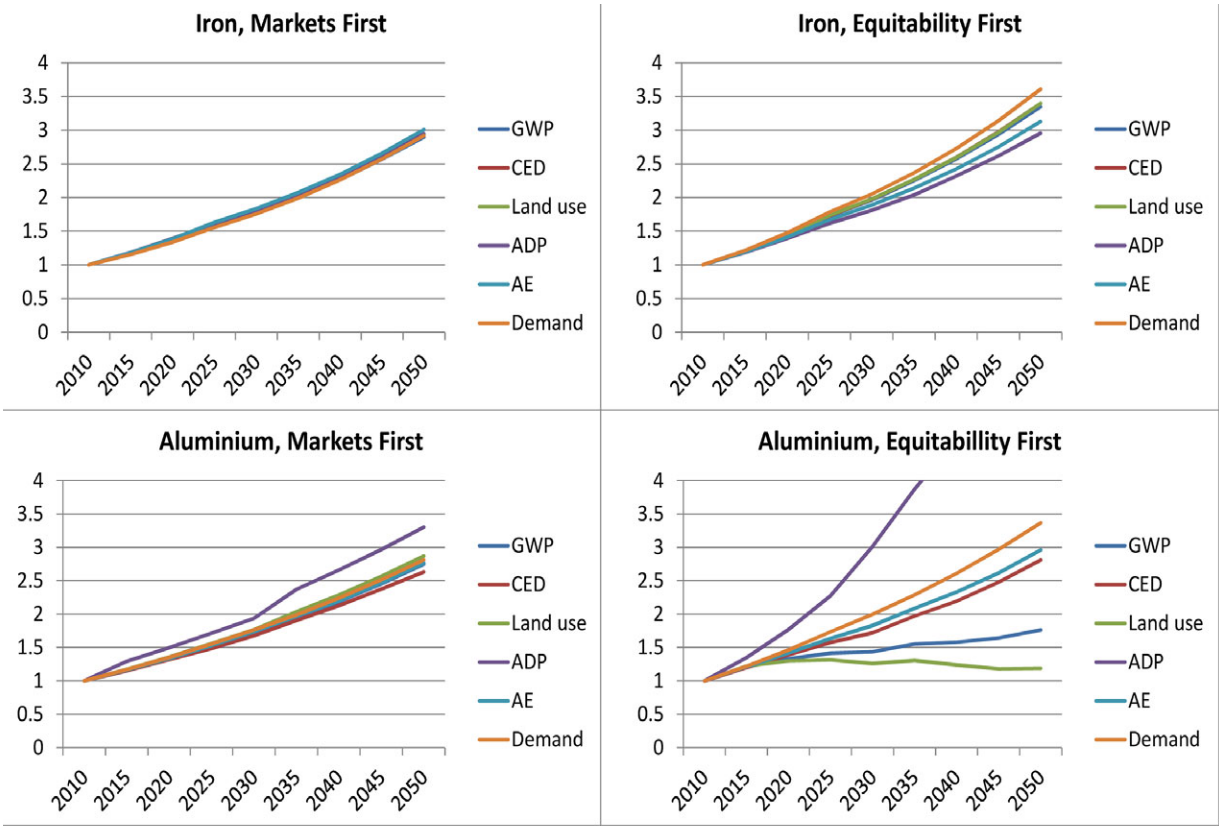

Figure 6 Trends in impact categories relative to demand, iron and aluminum, 2010–2050 (2010 = 1). ADP = abiotic depletion potential; AE = aquatic ecotoxicity (freshwater); CED = cumulative energy demand; GWP = global warming potential.

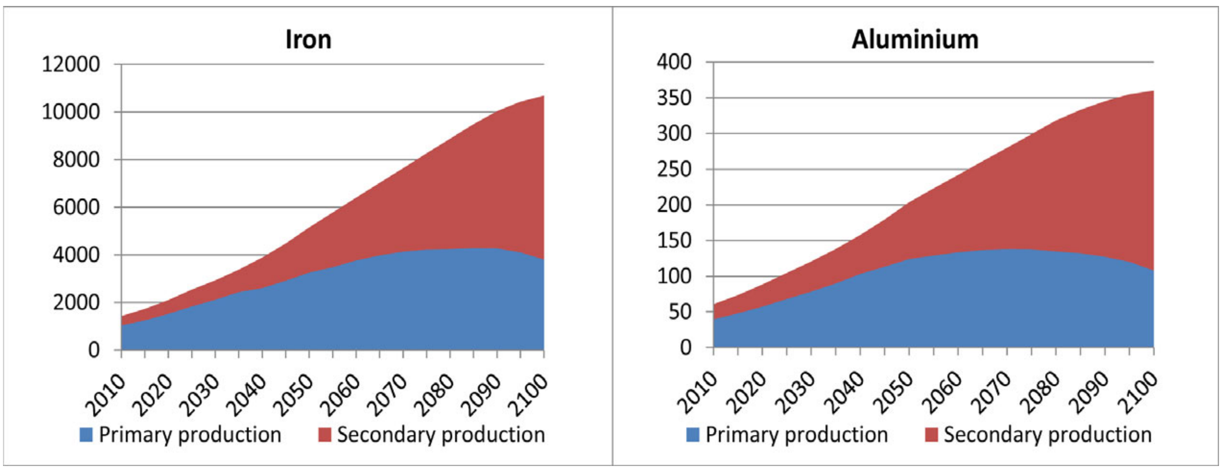

Figure 7 Primary and secondary supply of iron and aluminum under a Circular Economy scenario, 2010–2100 (10^9 kg / year).

the strongly decreasing emissions per kg, but also for iron where the per-kg emissions of primary production are reduced only slightly. The emissions peak for aluminum is expected around 2050, and the 2100 emission level under these assumptions is even below the 2010 level. For iron, the peak is reached considerably later, even after 2080. The conclusion, however, is that closing cycles for these metals seems to be the most powerful option of all to reduce GHG emissions. If this could be combined with a slowing down of demand, the reduction could be even more powerful, and could happen earlier.

Discussion and Implications

Above, we presented a method to estimate environmental consequences of demand scenarios for metals. In brief, the method aims at translating demand scenarios into

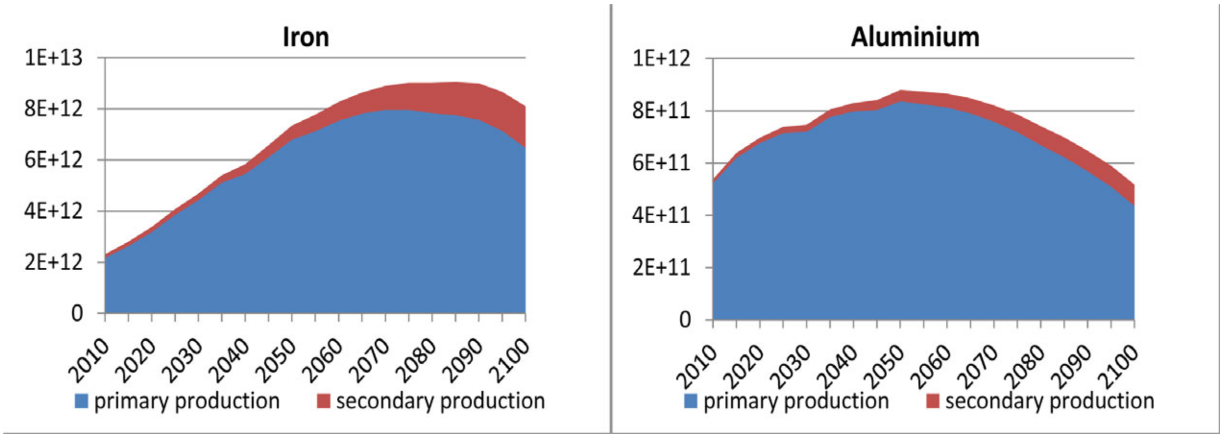

Figure 8 GHG emissions of iron and aluminum supply in the Circular Economy scenario, 2010–2100, in kg CO_2-equivalent per year. GHG = greenhouse gas; kg CO_2 = kilograms of carbon dioxide.

technology-specific supply scenarios. The steps taken are (1) calculation of cradle-to-gate environmental impacts of the production of 1 kg of a metal using LCA data and methods, (2) forward looking: specifying time series of impacts per kg for both primary and secondary production, based on changes in the background energy system, changes in ore grades, and improvements in energy efficiency, and (3) upscaling: multiplying the per-kg impacts with the production level over time for a number of different scenarios, taking into account the shares of primary and secondary production that may also change over time.

In all of these steps, we can identify uncertainties due to assumptions made, missing data, or uncertain causalities implied. Appendix 7 in the supporting information on the Web contains a description of the assumptions we made and of the uncertainties of various kinds related to those assumptions. It is important to address these, fill the gaps, and improve the database. We would like to emphasize, however, that scenarios should not be taken as accurate predictions, but regarded as explorations of potential future developments, to assess what might occur, what the consequences of different roads we could take might be, or which direction we could take to avoid unwanted situations. Taken as such, scenarios are powerful tools to obtain a better insight in the challenges that we may face, and a better understanding of how we could meet these challenges. The analysis above, despite uncertainties, identifies some important mechanisms and shows their relative importance, and as such offers valuable insights.

Nevertheless, improvements are possible, also in exploratory scenarios.

In the first place, it should be possible to obtain improved data on technological and geological variables, such as process efficiencies, recycling processes, and ore grade developments. The data on these subjects are not generally available, but may be present at the producers or the branch organizations. The analysis of the type we performed here would be very well served by making these data publicly available. To test the variability in outcomes due to data uncertainty, we performed a sensitivity analysis on some of the variables, presented in Appendix 8 in the supporting information on the Web. For zinc, we performed a sensitivity analysis on the influence of ore grade decline by comparing the scenarios with and without ore grade decline. The conclusion is that the variability bounded by those two versions of the scenario for GHG emissions is between 9% and 13%. The highest difference can be seen in the Equitability First scenario, where GHG emissions are reduced because of the changes in energy mix, and therefore the influence of other factors is relatively larger. For aluminum, a constant energy efficiency would lead to 1% to 10% higher outcomes for GHG emissions in 2050. In this case, the lowest difference is related to the Equitability First scenario, where efficiency improvements have a smaller influence due to the energy transition that is assumed. To improve the methodology by adding standard uncertainty and sensitivity analyses is a future task. For the present, we maintain that the general direction of the outcomes is rather robust.

A second issue is the narrow scope of the analysis. Many variables with environmental relevance are now ignored, such as the various inter-relations between the metals that exist: occurring together in ore bodies, being applied together in composite materials and in complex products, possibilities for recycling of waste streams from such complex products and materials, etc. Those issues now have not been included, but may be very relevant both for the demand scenarios and for their environmental implications. In a wider sense, nexus issues that could affect the environmental implications profoundly have been included only partly: the complex feedback loops between metals, energy and greenhouse gas emissions, or the water use for metals. In a life cycle perspective, resource needs and emissions related to metal production are part of the analysis, but the reverse relations, although they may be important, do not show. This field is still wide open for investigation.

A third issue is regionalization. Global averages are used for this analysis. In fact, energy mixes, but also mining operations, differ considerably from location to location. Also, it does not show the efforts made by, for example, the aluminum industry to make use of more renewable electricity sources—their global electricity mix has a higher share of hydropower than the general electricity mix. It would add value to take this in consideration and would make the results, especially for the present situation, more accurate.

With all these caveats, we think it is still possible to draw some conclusions from the analysis above. A first conclusion is that the increase in demand expected by Elshkaki and colleagues (2016b) will, by and large, lead to a similar increase in environmental impacts. Options to reduce the environmental impacts of metal production may slow down impact growth, but are generally not expected to result in decreased impacts. Metals will become even more important as a source of GHG emissions than they are already now. Under the Markets First scenario, GHG emissions from metal production will almost triple, while total global GHG emissions are expected to rise by a factor 1.5 in a business-as-usual scenario (IEA 2012). The share of metal production in GHG emissions thus will rise from 5% to 10%. Total GHG emissions under the Equitability First scenario will be reduced to 40% of the present level as a result of the energy transition (IEA 2012), which means GHG emissions from metal production would constitute up to 15% of the total in 2050. It is more likely, though, that this more-than-average increase of metal-related emissions is not even included in the energy/climate scenarios. This would imply that the GHG emissions in the energy and climate scenarios for 2050 may be substantially underestimated.

Moving toward a renewable energy system certainly is helpful to reduce the environmental impacts of metal production. However, even strong assumptions on reducing impacts from energy use cannot compensate the steeply rising demand over the next decades. The influence of other variables is minor compared to these two: Ore grade decline increases impacts per kg, but it appears to be a slow process, causing changes to happen very gradually over a long period of time, and the same is expected of efficiency improvements.

Iron dominates the environmental impacts of these seven metals, due to the sheer size of its production. At the same time, the iron-related per-kg impacts appear to be relatively unaffected by the different variables considered in the scenarios, even under a scenario with a profound transition toward a renewable energy system. This can be explained by the fact that mainly the electricity system is transformed. For iron, most of the emissions are process inherent and come from the use of cokes in steel making. This is not changed under any of the scenarios. This makes for a problem that is very difficult to solve: a tight coupling between the use of iron and steel and the use of fossil fuels, with the consequent GHG emissions.

For the other metals, emissions can indeed be substantially reduced via process improvements, but mostly via the energy transition. Especially metals with a high electricity demand benefit from this: aluminum, nickel, and manganese. For these metals, we see a decoupling of the energy requirements from GHG emissions. Overall, however, impacts increase also for these metals, albeit at a slower pace than demand. As the combined improvement of production and energy transition do not result in reduced GHG emissions for metal production, we have to look for other solutions.

A first solution might be to develop novel processes for metal production, especially for iron and steel production that use substantially less fossil fuels. These production processes basically have not changed for the last century. Smil (2016) discusses some novel processes which might reduce GHG emissions considerably when implemented at a large scale. However, he also cautions not to expect too much too soon in that direction.

A second solution could be to gear policy toward a considerable reduction of metal, especially iron and steel, use. However, steel is a material that is closely linked to infrastructure and the built environment. When economies develop, this goes hand in hand with a process of urbanization. In large parts of the world, this urbanization process is starting up; therefore, the expected increase in steel demand is not easily changed. Alternative construction materials could be considered. However, these materials, too, will have environmental impacts and it is not possible to know beforehand whether those impacts will be less than those related to metals.

A third solution, explored in this paper and very suitable for metals, could be to substantially increase the share of secondary production, or in other words to move toward a circular economy. An exercise to assess effectiveness shows that even for iron, and even in a situation of steep demand increase, this may reduce GHG emissions. This reduction, however, cannot be expected to happen before 2050 due to the long-term nature of the process. But on the longer term, we conclude that decoupling *primary* metals use from GDP would indeed be effective, and at the same time could still be in line with the social development ambitions of the Equitability First scenario. Increasing recycling rates to a high level may sound simple, but would in fact be another transformation of our society's metabolism, which would require changes through the whole materials cycle—mining and production processes, material design, product design, recycling systems, recycling technologies all linked to new information systems, and, last but not least, a considerable change in the policy system of barriers and incentives to allow it to happen.

For secondary supply to catch up with demand, it would also imply that the growth of the demand for metals has to stabilize. There are some indications that stock saturation occurs for iron and steel at a certain income level (Hatayama et al. 2010; Müller et al. 2006; Pauliuk et al. 2013; Smil 2016), which means the demand per capita will not grow anymore. Iron and steel are used mostly in basic applications related to construction and infrastructure (Hatayama et al. 2010; Hu et al. 2010). Once nations have built up their infrastructure, demand can go down to a level consistent with maintenance. For demand to stabilize at the global level, the global population would have to stabilize as well. This, too, is expected to occur as a result of welfare growth in most of the global-scale energy and climate-change scenarios, as it already has in the developed parts of the world.

Similar to climate change, the circular economy agenda for metals appears to be huge and long term, but definitely worthwhile pursuing as it appears to be the only way to substantially reduce emissions related to metal production. However, it all starts with a better understanding of the resource system, the dynamic interface between society and the environment. This is the research agenda related to the circularity transition, that the research community has to address urgently.

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Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information contains eight subsections (Appendices 1 to 8). Appendix 1 presents information on ore grade decline for copper, zinc, lead, and nickel. Appendix 2 shows efficiency improvements in production of iron and aluminum. Appendix 3 denotes electricity mixes under different energy scenarios compiled by the International Energy Agency. Appendix 4 presents the results of LCA impact assessment (including climate change, cumulative energy demand, land use, abiotic resource depletion, and aquatic eco-toxicity) per kg of metal. Appendix 5 shows scenario results for all impact categories discussed in Appendix 4, and Appendix 6 gives scenario results for the individual metals. Appendix 7 discusses the assumptions and uncertainties related to the calculations of impact. Finally, Appendix 8 contains a sensitivity analysis for assumptions on ore grade decline (zinc) and efficiency improvement (aluminum).