Environmental impacts of key metals' supply and low-carbon technologies are likely to decrease in the future

Harpprecht, Carina; van Oers, Lauran; Northey, Stephen A.; Yang, Yongxiang; Steubing, Bernhard

DOI
10.1111/jiec.13181

Publication date
2021

Document Version
Final published version

Published in
Journal of Industrial Ecology

Citation (APA)
Harpprecht, C., van Oers, L., Northey, S. A., Yang, Y., & Steubing, B. (2021). Environmental impacts of key metals' supply and low-carbon technologies are likely to decrease in the future. *Journal of Industrial Ecology*, *25*(6), 1543-1559. https://doi.org/10.1111/jiec.13181

DOI: 10.1111/jiec.13181

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

RESEARCH AND ANALYSIS

Environmental impacts of key metals' supply and low-carbon technologies are likely to decrease in the future

Carina Harpprecht[1,2] | Lauran van Oers[2] | Stephen A. Northey[3] | Yongxiang Yang[4] | Bernhard Steubing[2]

[1] Department of Energy Systems Analysis, Institute of Networked Energy Systems, German Aerospace Center (DLR), Stuttgart, Germany

[2] Institute of Environmental Sciences (CML), Leiden University, Leiden, The Netherlands

[3] Institute for Sustainable Futures, University of Technology Sydney, Ultimo, Australia

[4] Department of Materials Science and Engineering, Delft University of Technology (TU Delft), Delft, The Netherlands

Correspondence
Carina Harpprecht, Institute of Environmental Sciences (CML), Leiden University, P.O. Box 9518, 2300 RA Leiden, The Netherlands.
Email: c.i.harpprecht@cml.leidenuniv.nl

Editor Managing Review: Ichiro Daigo

Abstract

The environmental benefits of low-carbon technologies, such as photovoltaic modules, have been under debate because their large-scale deployment will require a drastic increase in metal production. This is of concern because higher metal demand may induce ore grade decline and can thereby further intensify the environmental footprint of metal supply. To account for this interlinkage known as the "energy-resource nexus", energy and metal supply scenarios need to be assessed in conjunction. We investigate the trends of future impacts of metal supplies and low-carbon technologies, considering both metal and electricity supply scenarios. We develop metal supply scenarios for copper, nickel, zinc, and lead, extending previous work. Our scenarios consider developments such as ore grade decline, energy-efficiency improvements, and secondary production shares. We also include two future electricity supply scenarios from the IMAGE model using a recently published methodology. Both scenarios are incorporated into the background database of ecoinvent to realize an integrated modeling approach, that is, future metal supply chains make use of future electricity and vice versa. We find that impacts of the modeled metal supplies and low-carbon technologies may decrease in the future. Key drivers for impact reductions are the electricity transition and increasing secondary production shares. Considering both metal and electricity scenarios has proven valuable because they drive impact reductions in different categories, namely human toxicity (up to –43%) and climate change (up to –63%), respectively. Thus, compensating for lower ore grades and reducing impacts beyond climate change requires both greener electricity and also sustainable metal supply. This article met the requirements for a Gold-Gold *JIE* data openness badge described at http://jie.click/badges

KEYWORDS
background changes, industrial ecology, life cycle assessment (LCA), prospective life cycle assessment, resources, scenarios

1 | INTRODUCTION

Although low-carbon technologies are considered essential for climate change mitigation (Bruckner et al., 2014), their environmental benefits are under debate because of their high metal intensity (Alonso et al., 2012; Fizaine & Court, 2015; Kleijn et al., 2011). Therefore, it is expected that a large-scale deployment of low-carbon technologies will lead to a drastic increase of metal demand in the future (de Koning et al., 2018; Roelich et al., 2014; Tokimatsu et al., 2018). This is of concern since metal production has severe environmental implications. It is not only highly energy intensive, consuming around 10% of global primary energy (Fizaine & Court, 2015; Rankin, 2011), and therefore a major contributor to global greenhouse gas (GHG) emissions. It also adds to other environmental pressures, such as ecosystem degradation or human health impacts (UNEP, 2013).

These environmental pressures could be further intensified in the future were there a continuation of declining mined ore grades as documented for copper, nickel, zinc, and lead (Crowson, 2012; Mudd, 2010; Mudd et al., 2017). Lower mined ore grades mean that more ore needs to be processed to produce the same amount of metal, leading to a rise in energy requirements and thus GHG emissions (Norgate & Haque, 2010; Norgate & Rankin, 2000). A decline in mined ore grades may result from various factors, such as, altered economic conditions, technology improvements (Ericsson et al., 2019; West, 2011), or from a depletion of higher grade ores due to rising metal demand as possibly induced by large-scale production of low-carbon technologies in the future.

Thus, metal and energy supply systems are closely interlinked, which is commonly referred to as the "energy-resource nexus" (Bleischwitz et al., 2017; Graedel & van der Voet, 2010; Le Blanc, 2015). Therefore, it is crucial to consider both systems when investigating future impacts of metal production and of low-carbon technologies in order to capture the interplay of the two systems and to avoid problem shifting.

A widely applied environmental assessment tool to analyze "potential impacts associated with a product" is life cycle assessment (LCA) (ISO, 2006). LCA models are often divided into so-called foreground and background systems. The foreground system typically consists of specific processes that are modeled by the practitioners. The background system typically consists of many more processes and is drawn from a life cycle inventory (LCI) database, for example, ecoinvent (Wernet et al., 2016). This background database provides the inputs to the foreground system such that the practitioners do not have to model all processes themselves.

While current product systems are in general analyzed using LCA, impacts of future systems are assessed using prospective LCA (Arvidsson et al., 2017; Pesonen et al., 2000). For prospective LCA, LCA models are adapted according to scenarios. To ensure consistency, scenarios are incorporated ideally into both fore- and background systems. While the foreground systems usually do reflect future scenarios, adapting the (much more numerous) processes in the background typically is not feasible. This is a prevalent shortcoming of prospective LCAs and is referred to as a "temporal mismatch" between the foreground and the background system (Arvidsson et al., 2017; Nordelöf et al., 2014; Sandén, 2007; Vandepaer & Gibon, 2018).

Metal supply systems in particular are mostly investigated regarding their current characteristics and current environmental performance (Elshkaki et al., 2016; Kuipers et al., 2018; Norgate & Haque, 2010; Norgate & Rankin, 2000; Nuss & Eckelman, 2014; Paraskevas et al., 2016). Yet, metal supply and its related impacts have been changing continually in the past, and are expected to continue doing so in the future (Rötzer & Schmidt, 2020). These changes are not only due to ore grade decline, which leads to higher energy intensity of mining activities, but also to technological innovation, which may lead to increased energy efficiencies, to regional differences between production locations (Northey et al., 2013), and to changes in secondary production shares or in shares of different production routes. For example, environmental impacts of pyrometallurgical copper production differ considerably from the hydrometallurgical copper production route (Azadi et al., 2020; Norgate & Haque, 2010; Norgate & Jahanshahi, 2010).

Van der Voet et al. (2019) developed detailed supply scenarios for seven major metals (copper, nickel, zinc, lead, iron, aluminum, and manganese) considering various relevant future developments, such as ore grade decline, energy-efficiency improvements, or changes in secondary production shares. They model future electricity systems by adapting electricity mixes in the background according to different energy scenarios (IEA, 2012). Thereby, all processes in the back- and foreground which have electricity as inputs receive the adapted future electricity, or the "futurized" electricity. However, their future metal supply chains are not integrated in the background database but modeled in the foreground, "on top" of the background database. This means that all other processes of the background database still make use of the non-future metal supply chains, such as, the future electricity supply sector (see Supporting Information S8, Section B.1 for a comparison of scenarios in foreground and background systems).

Other work investigated future impacts of low-carbon technologies taking an integrated scenario incorporation approach. Mendoza Beltran et al. (2020) and Cox et al. (2018) recently pioneered the integration of comprehensive model data into an LCA background database. They developed a Python-based software, Wurst (Mutel & Vandepaer, 2019), to incorporate comprehensive electricity supply scenarios from the integrated assessment model (IAM) from IMAGE (Integrated Model to Assess the Global Environment) into the background database (ecoinvent v3.3) (Stehfest et al., 2014). They confirm that electricity supply systems, or background systems in general, can be the decisive factors for environmental benefits of low-carbon technologies.

To date, a few studies combined future electricity and metal supply scenarios within an LCI database. The New Energy Externalities Development for Sustainability (NEEDS) project generated prospective LCIs by incorporating energy supply and material production scenarios into ecoinvent version 1.3. The most comprehensive and recent work is THEMIS (Technology Hybridized Environmental-Economic Model With Integrated Scenarios) (Gibon et al., 2015; Hertwich et al., 2015). Using hybrid input–output LCA models, THEMIS integrates various scenarios, such as NEEDS, future electricity mixes from the International Energy Agency (IEA), and material production scenarios, into ecoinvent v2.2 to build prospective LCIs. The material production scenarios assume one development, namely a reduction of energy inputs during productions due to technological-efficiency improvements.

Metal supply scenarios considering possible future developments, such as ore grade decline and shares of different production routes, have not been incorporated into a recent background database yet, despite the substantial environmental contributions of metal supply to impacts of technology productions. Most of the research so far focused on incorporating detailed energy scenarios, yet did not model diverse changes in future metal production systems (Arvesen et al., 2018). Moreover, comprehensive metal supply scenarios have not been incorporated into an LCI database in combination with electricity supply scenarios to create a more consistent background database suitable for accounting for interdependencies, for instance, due to the energy-resource nexus.

This study aims to incorporate metal supply scenarios, which model several future developments, as well as scenarios for an energy transition directly into the ecoinvent 3.5 database. This integrated scenario incorporation allows for interactions between these two modified supply chains, and therefore accounts for the energy-resource nexus. We aim to answer the following research questions:

1. What are the environmental impacts of the future production of copper, nickel, zinc, and lead?
2. How do future metal supply changes and electricity supply changes influence future impacts of metal supply and of low-carbon technologies?

To achieve this, we build on approaches and scenarios from previous research as follows. We use the work of Mendoza Beltran et al. (2020) to incorporate electricity scenarios from IMAGE. For the metal supply scenarios, we build on and extend the study of van der Voet et al. (2019), which provides comprehensive supply scenarios for seven metals. We choose four metals whose global GHG emissions are among the top 10 of all metals (Nuss & Eckelman, 2014) and for which ore grade decline has been documented: copper, nickel, zinc, and lead. We further extend the scenarios of van der Voet et al. (2019), adapt them from ecoinvent version 2.2 to version 3.5, and integrate them into the background database. The metal supply scenarios form the main focus of our work. It is important to stress that our scenarios should not be seen as predictions but rather as an exploration of possible future developments and their role for future environmental performances of a product system.

2 | METHODS

2.1 | Approach overview

We modeled future metal supply (MS) scenarios for four metals until 2050: copper (Cu), nickel (Ni), zinc (Zn), and lead (Pb). To estimate future developments in metal supply, we chose key factors influencing future changes, and describe them via five variables: (1) mined ore grade, (2) primary production locations, (3) energy-efficiency improvements of metal refining, (4) shares of primary production routes, and (5) shares of primary and secondary production.

Furthermore, we added electricity supply (ES) scenarios which describe possible future energy systems using a recently published approach by Mendoza Beltran et al. (2020).

Considering both metal and electricity supply scenarios, we investigated how environmental impacts of future metal supply and low-carbon technologies may develop in the future, and examined the key drivers for those future impact changes. Furthermore, we also assessed the effect of metal and electricity supply changes on key applications of a low-carbon economy, such as electricity production from photovoltaics (PV) and wind, as well as the production of Li-ion batteries, and transport with an EV.

The scenarios were assessed for the time period of 2010–2050 in intervals of 5 years using Brightway2 (Mutel, 2017a, 2018). They were modeled by modifying the background database, that is, ecoinvent version 3.5, allocation, cut-off by classification (Ecoinvent Center, 2018; Wernet et al., 2016). This means that already existing activities in ecoinvent were changed and/or new activities were added according to scenario data (see Supporting Information S8, Section B.1). Thereby, future versions of ecoinvent are created for each scenario year representing future systems.

This method increases temporal consistency through the creation of future background databases, and it realizes an integrated approach since process modifications become effective in the whole database. Hence, this approach allows for interactions between the metal and electricity supply systems: future metal supply chains use future electricity and vice versa, thereby accounting for interlinkages due to the energy-resource nexus.

2.2 | Metal supply scenarios

The five variables of our metal supply scenarios address different production stages of metal supply chains, from mining (variable 1, ore grade decline) over refining (e.g., variable 3, energy-efficiency improvements) to global market shares (e.g., variable 5, primary/secondary production shares).

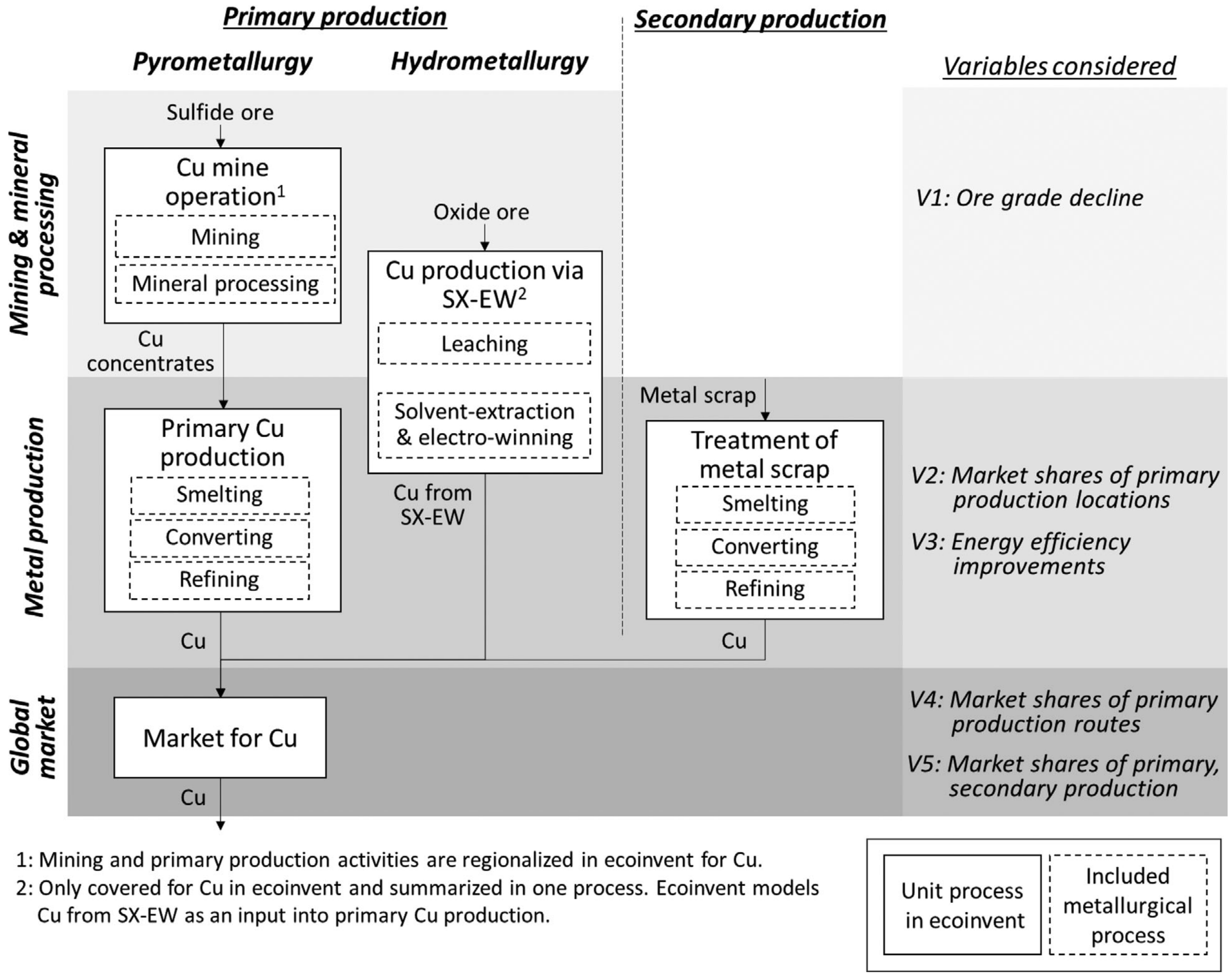


FIGURE 1 Structure of the copper supply chain in ecoinvent 3.5 and the modeled variables at each supply stage
Structure of the copper supply chain in ecoinvent 3.5, the included metallurgical processes, and the modeled variables at each supply stage. Copper mine operation produces a copper concentrate of 30%. Primary copper production refines this concentrate producing refined copper. The supply chains of the other metals are given in Supporting Information S8 (Figures B.3– B.7). Cu, copper; SX-EW, solvent extraction and electro-winning; V, variable

Figure 1 illustrates how ecoinvent represents metal supply chains at the example of copper and at which production stage the variables are incorporated. It distinguishes between three stages: (1) mining and mineral processing which produces copper concentrates of 30%; (2) metal production which comprises copper smelting, converting, and refining, to supply refined copper; and (3) a global market. Furthermore, we distinguish between pyrometallurgical and hydrometallurgical primary production of copper, and between primary and secondary production shares.

The supply chains of the other metals are described in Supporting Information S8 (Section B.2). For nickel, we model two different types which cover the majority of the nickel market (van der Voet et al., 2019). Those are "nickel" with a purity of 99.5%, and the less pure "ferronickel," which contains 25% nickel (see Supporting Information S8, Section B.2.2).

Primary metal supply (PMS) changes are represented by variables 1 to 4, while variable 5 models secondary metal supply (SMS) changes. The main focus of our metal supply scenario lies on ore grade decline (variable 1). Therefore, this variable is modeled for all four metals, while the rest of the primary supply variables, variables 2–4, are only modeled for copper. Copper is of special interest given its expected demand growth and relevance for low-carbon technologies (Deetman et al., 2018; Hertwich et al., 2015). Variable 5 is modeled for copper, nickel, and lead. Zinc and ferronickel are excluded for variable 5 as their ecoinvent models do not include secondary supply activities.

The data sources used for each variable are shown in Table 1. Differences to the scenarios of van der Voet et al. (2019) mostly lie in the addition of regionalized copper scenarios for variables 1 and 2, and in the adaptation of the variable models to the newer supply chains in ecoinvent v3.5. Each variable is further explained in the following paragraphs with its data being accessible via a repository (Harpprecht et al., 2021). The generated scenarios are then illustrated in the results section in Figure 2.

TABLE 1 Variables and data sources for the generation of metal supply scenarios

Variable	Metal	Data source	Information
1. Ore grade decline	Ni, FeNi	Mudd and Jowitt 2014	Historical ore grades to create a regression model to project future global ore grades
		Norgate and Jahanshahi 2006	Ore grade-energy requirement relation
	Zn, Pb	Mudd, Jowitt, and Werner 2017	Historical ore grades to create a regression model to project future global ore grades
		Valero, Valero, and Domınguez 2011	Ore grade-energy requirement relation
	Cu	*Mudd and Jowitt 2018*	*Regionalized instead of global ore grades, historical data*
		Northey et al. 2014	*Regionalized instead of global ore grade scenarios based on supply–demand models*
		Northey, Haque, and Mudd 2013	Ore grade-energy requirement relation
2. Market shares of production locations	Cu	*Northey et al. 2014*	*Regionalized future production scenarios based on supply–demand models*
3. Energy efficiency improvements	Cu	Kulczycka et al. 2016	Future energy inputs for pyrometallurgical Cu production
4. Market shares of primary production routes	Cu	International Copper Study Group 2018	*More recent* historical data on hydro- and pyrometallurgical production shares
5. Market shares of primary, secondary production	Cu, Ni, Pb	Elshkaki et al. 2018	Global shares of primary, secondary supply

Crucial updates compared to the models of van der Voet et al. (2019) are highlighted in italics. Cu, copper; FeNi, ferronickel; Ni, nickel; Pb, lead; Zn, zinc.

2.2.1 | Stage 1: Metal mining

Variable 1: Ore grade decline and energy requirements

For all metals, we calculate future ore grade decline, the caused change in energy requirements and in other inputs/outputs in two steps, similarly to van der Voet et al. (2019) and Kuipers et al. (2018). Detailed explanations are provided in Supporting Information S8 (Section B.3.1).

1. Defining current, $G(t_0)$, and future ore grades, $G(t > t_0)$:

   We estimate current, $G(t_0)$, and future ore grades, $G(t > t_0)$, with an ore grade model, $G(t)$. t_0 is the year for each ecoinvent mining process.

   For nickel, zinc, and lead, $G(t)$ is defined via metal-specific regression models of van der Voet et al. (2019), which are based on historical data (Table 1).

   For copper, future ore grades, $G(t > t_0)$, are defined using data from regionalized models of Northey et al. (2014), specifically their "country-dynamic" scenario. They model copper production amounts and ore grades for 83 regions from 2010 to 2100 with the Geologic Resources Supply–Demand Model (GeRS-DeMo) developed by Mohr (2010). We match their 83 regions to the 6 pyrometallurgical copper production regions in ecoinvent, and use the production shares of the individual countries as weighing factors to derive an average ore grade per region (see Supporting Information S8, Equation B.10 and Harpprecht et al. (2021)). For $G(t_0)$, historic ore grade data is taken from Mudd and Jowitt (2018).
2. Defining current, $E(t_0)$, and future energy requirements, $E(t > t_0)$, with an ore grade–energy relation, $E(G)$:

   The ore grade–energy relations are taken from van der Voet et al. (2019), who generated them from the literature (Table 1) for each metal. With $G(t_0)$, $G(t > t_0)$, and $E(G)$, we define $E(t_0)$ and $E(t > t_0)$ as:

$$E(t_0) = E(G(t_0)), \tag{1}$$

$$E(t > t_0) = E(G(t > t_0)). \tag{2}$$

Subsequently, we define a factor, $\delta_E(t, t_0)$, which describes how future energy requirements, $E(t > t_0)$, will change relative to current energy requirements, $E(t_0)$ (see Supporting Information S8, Section B.3.1). As a simplification, which was also used by van der Voet et al. (2019), we assume that this factor, $\delta_E(t)$, can be applied as a proxy to also model the increase and decrease of all other in- and outflows of the mining process (see Supporting Information S8, Section D.1 for a discussion).

2.2.2 | Stage 2: Primary metal production

Variable 2: Market shares of primary production locations

Since production characteristics, such as energy sources or waste treatments, are country-specific, environmental impacts associated with primary copper production vary largely between countries (Beylot & Villeneuve, 2017) (Supporting Information S8, Figure B.15).

We apply the future production shares modeled by Northey et al. (2014) to the production shares per ecoinvent region of copper primary production using the regional match from variable 1 (see Supporting Information S8, Section B.3.2).

Variable 3: Energy-efficiency improvements during smelting and refining

We model a decrease of required electricity and natural gas inputs (-1.77% and -1.5% per year) during smelting and reduction processes within the pyrometallurgical primary production route (Supporting Information S8, Figure B.16) with an exponential regression of van der Voet et al. (2019), which was based on projections of Kulczycka et al. (2016).

2.2.3 | Stage 3: Market shares of global metal markets

Variable 4: Market shares of primary production routes

Copper is predominantly produced in two primary production routes, pyrometallurgy and hydrometallurgy. Since their environmental impacts differ considerably (Norgate & Haque, 2010; Norgate & Rankin, 2000), we build a scenario for their future market shares. While Kuipers et al. (2018) applied a linear regression model based on historic data showing increasing hydrometallurgical shares, we apply an exponential regression model taking into account the recent continuous declines of hydrometallurgical shares (International Copper Study Group, 2018). Thus, we assume a decrease over time in the share of copper production from hydrometallurgical processing of oxide ores, in contrast to the increase in Kuipers et al. (2018). This is in line with recent forecasts for Chile (COCHILCO, 2019), globally the largest copper miner (see Supporting Information S8, Section B.3.4).

Variable 5: Market shares of primary and secondary production

Primary and secondary production shares are projected using the models of Elshkaki et al. (2018) (see Supporting Information S8, Section B.3.5), which they based on the Fourth Global Environmental Outlook scenario set (GEO-4) by the United Nations Environmental Programme (UNEP) (UNEP, 2007). In line with van der Voet et al. (2019), we select the "Market First" scenario of Elshkaki et al. (2018), since it is a business-as-usual scenario. The scenario is incorporated into the global markets of copper, nickel (99.5%), and lead.

2.3 | Electricity supply scenarios

The electricity supply scenarios are taken from Mendoza Beltran et al. (2020), who use IMAGE 3.0 as scenario source (Stehfest et al., 2014) (see Supporting Information S8, Section B.4). As an integrated assessment model (IAM), IMAGE models the human system with a focus on energy and land use systems. Mendoza Beltran et al. (2020) use the Shared Socioeconomic Pathways (SSPs) of IMAGE (O'Neill et al., 2014). Each pathway consists of a baseline scenario, that is, how the future develops without additional climate policies, and various mitigation scenarios (Riahi et al., 2017). From those pathways, we select SSP2, the "middle-of-the-road" pathway in which current trends continue without considerable change (Fricko et al., 2017; van Vuuren et al., 2017). From SSP2, we take its baseline and its strongest mitigation scenario, SSP2 and SSP2-2.6. They represent the two extremes within SSP2 (Fricko et al., 2017). SSP2-2.6 describes the strongest mitigation efforts to reach the two-degree target of 450 ppm CO_2eq.

2.4 | Incorporating metal and electricity supply scenarios

To analyze the effect of the MS variables and ES scenarios, we adapt the background database, that is, ecoinvent, with the scenarios described in Table 2.

The scenario data is incorporated with Presamples (Lesage, 2019; Lesage et al., 2018) and Wurst (Mutel, 2017b) for the MS and ES scenarios, respectively (see Supporting Information S8, Section B.5).

TABLE 2 Future scenarios modeled for the prospective LCAs from 2010 to 2050 in time steps of five years

Description	MS variables	ES scenario	Scenario
MS	1–5	n.a.	MS
MS, only primary production changes	1–4	n.a.	PMS
MS, only secondary production changes	5	n.a.	SMS
ES	n.a.	SSP2	ES-BAU
ES	n.a.	SSP2-2.6	ES-Mitigation
ES + MS	1–5	SSP2	MS + ES-BAU
ES + MS	1–5	SSP2-2.6	MS + ES-Mitigation

BAU, business-as-usual; ES, electricity supply; MS, metal supply; PMS, primary metal supply; SMS, secondary metal supply; SSP, shared socioeconomic pathway.

TABLE 3 Functional units taken from ecoinvent 3.5 for metal supply and metal applications

Category	Reference flow	Process	Region
Global metal markets	1 kg of copper	Market for copper	GLO
	1 kg of nickel, 99.5% Ni	Market for nickel, 99.5%	GLO
	1 kg of ferronickel, 25% Ni	Market for ferronickel, 25% Ni	GLO
	1 kg of zinc	Market for zinc	GLO
	1 kg of lead	Market for lead	GLO
Metal applications	1 kWh electricity, high voltage	Market group for electricity, high voltage	GLO
	1 kWh electricity, low voltage	Electricity production, PV, 3 kWp slanted-roof installation, multi-Si	CH
	1 kg of Li-ion battery prismatic	Battery production, Li-ion, prismatic	GLO

CH, Switzerland; GLO, global; kWp, kilowatt peak; Li, lithium; Ni, nickel; PV, photovoltaics.

2.5 | Scenario evaluation

2.5.1 | Functional units

The effect of our scenarios on the future environmental performances of the five metals' supply as well as of electricity supply and low-carbon technologies are assessed using functional units from ecoinvent (Table 3). We present results for two out of the five low-carbon technology examples: electricity production from PV and production of a Li-ion battery (see Supporting Information S8, Section B.6.1). The functional units use ecoinvent, updated with the scenario data, as background.

2.5.2 | Impact assessment

Impacts are assessed for six impact categories: climate change (CC); cumulative energy demand, fossil (CEDF); particulate matter formation (PMF); photochemical oxidant formation (POF); human toxicity (HT); and metal depletion (MD). The former five are relevant for impacts related to energy generation, while the latter two additionally address metal supply impacts. This choice is in accordance with other studies (Bauer et al., 2015; Gibon et al., 2017; Mendoza Beltran et al., 2020; Nordelöf et al., 2014).

We apply the IPCC 2013 (time horizon 100 years) characterisation model from IPCC (2013) for climate change, but include biogenic carbon as described by Mendoza Beltran et al. (2020) (see Supporting Information S8, Section B.6.2). RECIPE 2008 at the mid-point level serves as characterisation model for all other impact categories (Goedkoop et al., 2013).

3 | RESULTS

3.1 | Development of metal supply variables

Figure 2 illustrates the development of the five variables that feed into the MS scenarios. The modeled decline of mined ore grades into the future (Figure 2a) results in a corresponding rise in energy requirements (Figure 2b), with the highest change of +78% being for lead from 2010 to 2050.

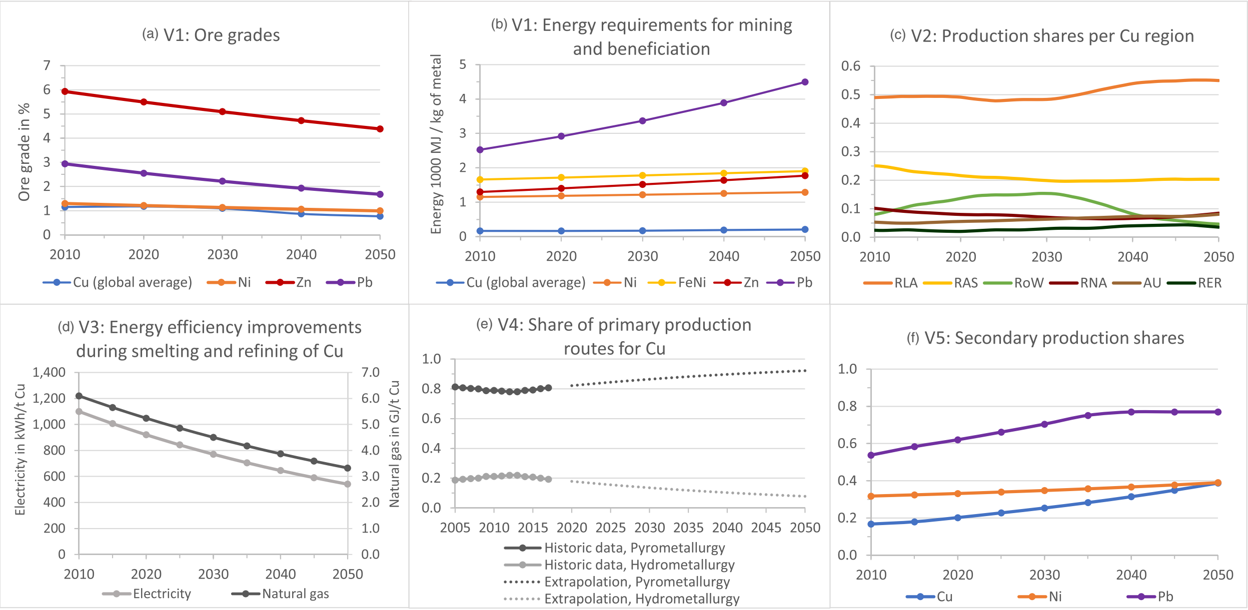


FIGURE 2 Overview of applied metal supply scenarios for the five metal supply variables
Overview of the applied metal supply scenarios for the five metal supply variables (for a detailed description of each variable, see Supporting Information S8, Section B.3). The scenario data is accessible via a repository (Harpprecht et al., 2021). For Cu, variable 1, only the global average is shown. The regionalized variables are provided in Supporting Information S8 (Figure B.13). Underlying data used to create this figure can be found in Supporting Information S2. AU, Australia; Cu, copper; GLO, global; Ni, nickel; Pb, lead; RAS, Asia; RER, Europe; RLA, Latin America and the Caribbean; RNA, Northern America; RoW, Rest of the World; V, variable; Zn, Zinc

For copper and nickel energy requirements increase by +24.1% and +11.9%, respectively. Variable 3 shows substantial reductions in energy consumption during primary production (smelting and refining) of copper. While ore grade decline, variable 1, will cause an intensification of impacts due to the increasing energy requirements, variables 3 to 5 are expected to have a diminishing effect. The subsequent results show the effect of the states of variables from Figure 2.

3.2 | Future impacts of metal and electricity supply

Figure 3a shows prospective LCA results for all metals per kg of metal supply. For all metals, a general downward trend becomes apparent especially under the MS + ES-Mitigation scenario. For the MS + ES-BAU scenario, ferronickel and zinc form an exception, since their models do not include increasing secondary supply shares which would have a diminishing effect on impacts. Copper shows the highest decreases which could be due to the fact that it has more variables incorporated which potentially leads to more drastic changes.

Figure 3b illustrates how the electricity scenario ES-Mitigation reduces climate change and human toxicity impacts of electricity supply by -98% and -79% by 2050, but on the other hand more than doubles metal depletion impacts. The MS scenarios lower this steep rise of metal depletion from +105% in 2050 to only +95% (see Supporting Information S8, Figure C.6). Thus, increases in metal depletion impacts of a greener electricity supply cannot be compensated by our modeled metal supply improvements.

3.3 | Drivers of future impacts

Figure 4 illustrates the relative impact changes between 2010 and 2050 for both the modeled metal markets and the applications of electricity production from PV and the production of a Li-ion battery. The results are given for different combinations of scenarios as defined in Table 2.

3.3.1 | Future metal supply impacts

Incorporating PMS variables causes an impact increase for all metals apart from copper. Lead reveals the strongest increase since it also experiences the strongest decline in ore grade and consequently the highest intensification of energy requirements from 2010 to 2050. Copper's

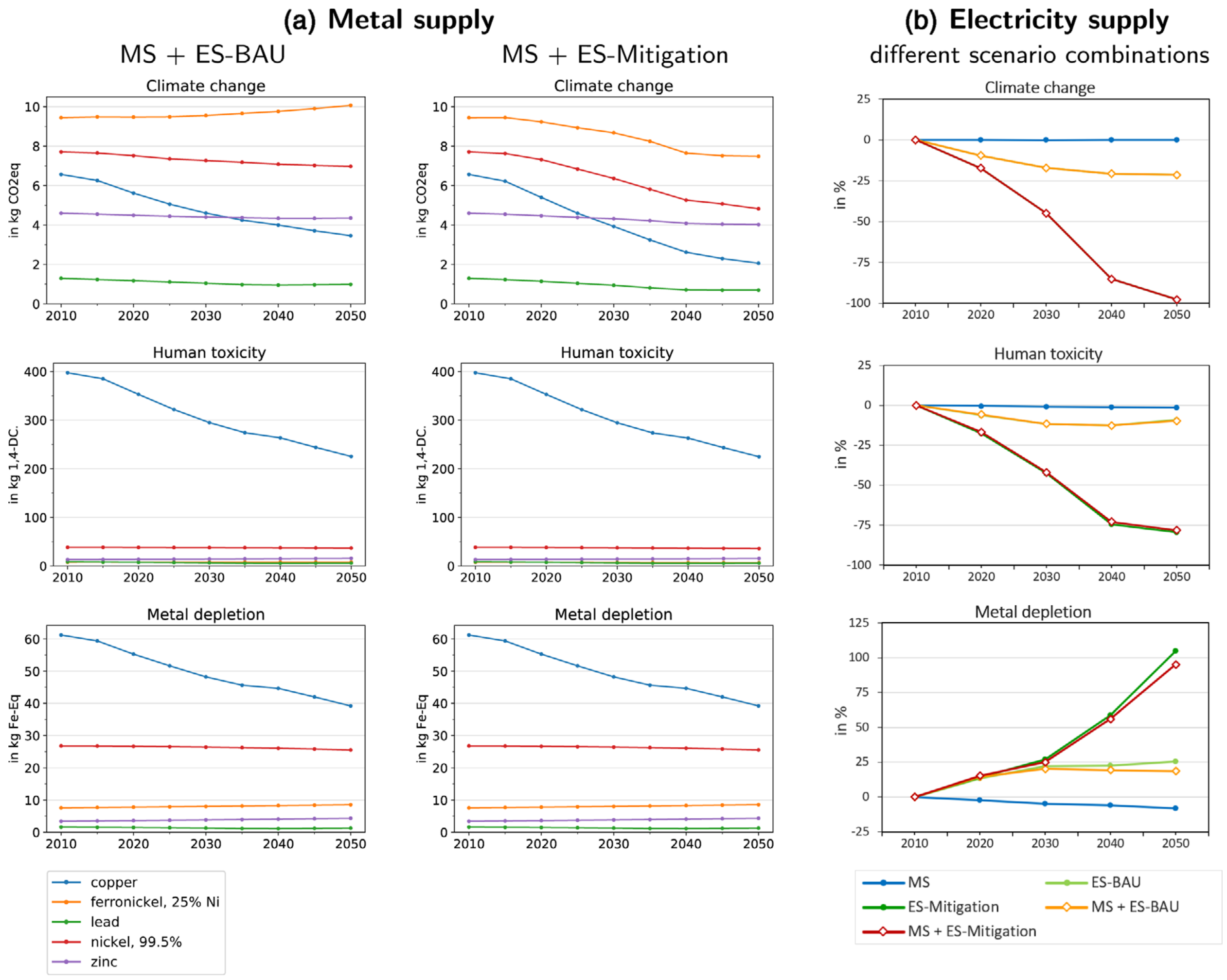


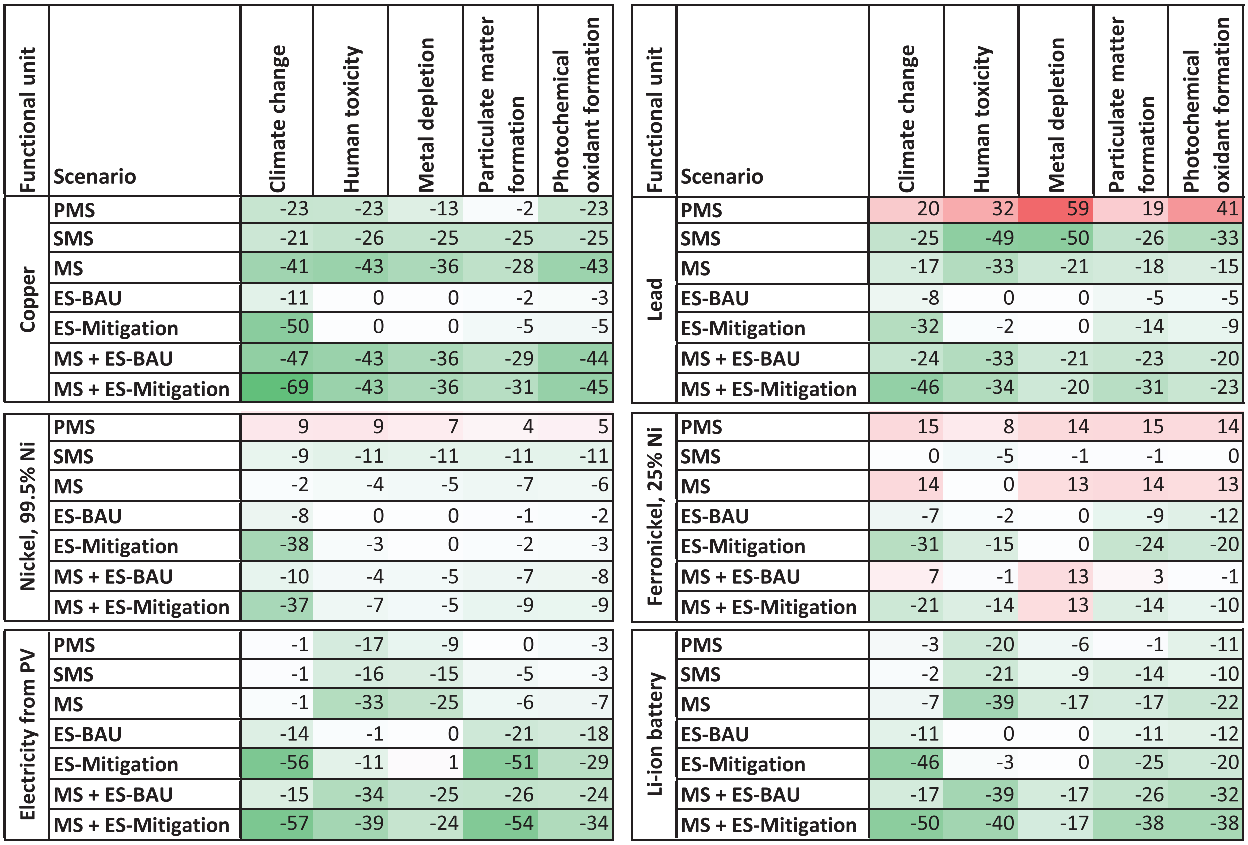
FIGURE 3 Prospective LCA results for metal and electricity supply under different scenario combinations.
(a) Prospective LCA results for the five global metal markets per 1 kg of metal supplied
All metal supply variables are included in combination with electricity scenarios; either the business-as-usual electricity scenario (ES-BAU); or the mitigation electricity scenario (ES-Mitigation). More impact categories are presented in Supporting Information S8 (Section C.1). (b) Prospective impact developments per 1 kWh from the global electricity mix under the two electricity (ES) and metal supply (MS) scenarios, relative to impacts in 2010. Decreasing trends due to the electricity supply scenarios take place for all impact categories apart from metal depletion, see Supporting Information S8, Figure C.6. Underlying data used to create this figure can be found in Supporting Information S4. BAU, business-as-usual; DC, 1,4-dichlorobenzene equivalents; ES, electricity supply; Fe-eq, iron equivalent; MS, metal supply

falling PMS impacts can be explained by the fact that its PMS models comprise several variables which have a diminishing effect on impacts, such as variable 3, that is, reducing energy inputs during smelting and refining, and variable 4, that is, decreasing hydrometallurgical production shares. The other metals' PMS models only consist of the ore grade decline model which generally increases impacts. Thus, the development of the copper variables 2 to 4 overcompensate for growing impacts associated with falling mined ore grades, which is further investigated later in this article.

Increasing secondary supply shares, as done for the SMS scenario for copper, nickel, and lead, proves to decrease impacts associated with these metals' total supply, that is, from the average market which includes primary and secondary supply.

From ferronickel's SMS results, we can see an effect of the integrated scenario incorporation: impacts change although ferronickel's SMS variables are unaltered. Since the SMS variables are incorporated for all metals at the same time, this change is induced by other metals' SMS changes, specifically by copper (see Supporting Information S8, Figure C.7).

Another crucial feature of our integrated approach is the interaction between scenarios when several scenarios are incorporated jointly. This can be seen, for example, from the MS results: when all MS variables are incorporated (PMS + SMS variables), results of PMS and SMS scenarios cannot be added up to get the MS results. Therefore, impact changes of individual variables cannot reflect the joint effect of their combination. This phenomenon can be explained by an example (see, e.g., lead): if ore grades decline in primary production (PMS), but primary production



Functional unit	Scenario	Climate change	Human toxicity	Metal depletion	Particulate matter formation	Photochemical oxidant formation
Copper	PMS	-23	-23	-13	-2	-23
	SMS	-21	-26	-25	-25	-25
	MS	-41	-43	-36	-28	-43
	ES-BAU	-11	0	0	-2	-3
	ES-Mitigation	-50	0	0	-5	-5
	MS + ES-BAU	-47	-43	-36	-29	-44
	MS + ES-Mitigation	-69	-43	-36	-31	-45
Nickel, 99.5% Ni	PMS	9	9	7	4	5
	SMS	-9	-11	-11	-11	-11
	MS	-2	-4	-5	-7	-6
	ES-BAU	-8	0	0	-1	-2
	ES-Mitigation	-38	-3	0	-2	-3
	MS + ES-BAU	-10	-4	-5	-7	-8
	MS + ES-Mitigation	-37	-7	-5	-9	-9
Electricity from PV	PMS	-1	-17	-9	0	-3
	SMS	-1	-16	-15	-5	-3
	MS	-1	-33	-25	-6	-7
	ES-BAU	-14	-1	0	-21	-18
	ES-Mitigation	-56	-11	1	-51	-29
	MS + ES-BAU	-15	-34	-25	-26	-24
	MS + ES-Mitigation	-57	-39	-24	-54	-34

Functional unit	Scenario	Climate change	Human toxicity	Metal depletion	Particulate matter formation	Photochemical oxidant formation
Lead	PMS	20	32	59	19	41
	SMS	-25	-49	-50	-26	-33
	MS	-17	-33	-21	-18	-15
	ES-BAU	-8	0	0	-5	-5
	ES-Mitigation	-32	-2	0	-14	-9
	MS + ES-BAU	-24	-33	-21	-23	-20
	MS + ES-Mitigation	-46	-34	-20	-31	-23
Ferronickel, 25% Ni	PMS	15	8	14	15	14
	SMS	0	-5	-1	-1	0
	MS	14	0	13	14	13
	ES-BAU	-7	-2	0	-9	-12
	ES-Mitigation	-31	-15	0	-24	-20
	MS + ES-BAU	7	-1	13	3	-1
	MS + ES-Mitigation	-21	-14	13	-14	-10
Li-ion battery	PMS	-3	-20	-6	-1	-11
	SMS	-2	-21	-9	-14	-10
	MS	-7	-39	-17	-17	-22
	ES-BAU	-11	0	0	-11	-12
	ES-Mitigation	-46	-3	0	-25	-20
	MS + ES-BAU	-17	-39	-17	-26	-32
	MS + ES-Mitigation	-50	-40	-17	-38	-38

FIGURE 4 Prospective LCA results for the global metal markets of copper, nickel, and lead, and for low-carbon technologies Prospective LCA results for the functional units of the global metal markets of copper, nickel, and lead, and of low-carbon technologies, that is, electricity production from PV and production of a Li-ion battery (see Table 3). Results are given for 2050 as relative changes (in %) compared to the respective LCA scores in 2010. Scenario variables are given in Table 2. Results for CEDF, zinc, for more technologies, for electricity supply, and in the form of a detailed time series are provided in Supporting Information S8, Figures C.5 and C.6. Underlying data used to create this figure can be found in Supporting Information S5. BAU, business-as-usual; ES, electricity supply; Li, lithium; MS, metal supply; Ni, nickel; PMS, primary metal supply; PV, photovoltaics; SMS, secondary metal supply

shares are partly replaced by secondary production (SMS), then the PMS scenario has a smaller effect on MS (PMS + SMS), since its share has been reduced.

MS impacts are only reduced for copper, nickel, and lead, while for zinc and ferronickel MS impacts rise (see Supporting Information S8, Figure C.5). The reason is that zinc and ferronickel are lacking secondary production improvements in our SMS scenarios which could compensate for impact increases of the PMS scenarios as is the case for lead and nickel.

As expected, both ES scenarios achieve substantial impact reductions for all metals. These are strongest for the ES-Mitigation scenario and in the category of climate change, with the highest decrease of -50% for copper. Yet, it stands out that they barely influence impacts of human toxicity and metal depletion. The reason is that impacts of those categories are primarily caused by flows occurring during mining which ES scenarios do not affect. These flows are sulfidic tailings for human toxicity and the extraction of metal ore from the ground in the case of metal depletion (see Supporting Information S8, Section C.3.1). The same applies to PMF and POF, as here electricity-related emissions play only a minor role compared to emissions from mining, metal refining, and heat supply.

When combining MS and ES scenarios, we can see the interplay of impact changes from both scenarios. They either complement each other, meaning one achieves impact reductions in a category where the other one has little effect, or they add to each others impact changes. As explained before, adding up impact changes from the individual scenarios cannot describe their combined effect due to the interaction of scenarios. In most cases, the combination of MS and ES scenarios achieves higher impact reductions than an individual scenario. For all metals, the energy scenario is the decisive driver for impact reductions in climate change, whereas human toxicity and metal depletion results are driven by MS scenarios. In the case of ferronickel and zinc, ES scenarios can only partly compensate for the rising impacts due to MS changes. For ferronickel, impacts are driven more from heat supply than from electricity supply (see Supporting Information S8, Figure C.11).

3.3.2 | Future impacts of low-carbon technologies

For the metal applications, that is, electricity produced from PV and the production of a Li-ion battery (for results for other technologies see Supporting Information S8, Figure C.6), results show a very similar pattern as for the metal markets. While ES scenarios primarily decrease climate change, they barely influence human toxicity and metal depletion impacts, yet those are in turn considerably lowered by MS scenarios.

Although MS scenarios have a considerable influence on climate change impacts for the metal markets, this is not the case for low-carbon technologies. This reveals that future changes of energy requirements of metal supply play only a minor role for climate change impacts of low-carbon technologies. In contrast, human toxicity and metal depletion impacts of low-carbon technologies are largely dominated by the performance of metal supply. Specifically, those impacts are mostly caused by metal mining activities, that is, human toxicity by sulfidic tailings and metal depletion by the metal extraction (see Supporting Information S8, Section C.3.2). This furthermore explains why ES scenarios have, as for the metal markets, little effect on these categories. The ES-Mitigation scenario demonstrates again its strong power via considerably higher impact reductions than the ES-BAU scenario with its maximum at 56% for climate change.

As before, combining both MS and ES scenarios reveals how the two scenarios complement each other with impact reductions in different categories. As a result, impacts are considerably reduced for almost all categories. The smallest changes always appear for metal depletion.

Looking at the applications' impact changes due to MS, the question arises which metal mainly causes those changes. An analysis presented in Supporting Information S8 (Section C.2.3, Figures C.8– C.10) reveals that clearly the copper MS scenarios are driving the MS-caused change of the technologies' future impacts. All other metals' scenarios show almost no effect on future impact changes of metal applications.

3.4 | Drivers of future copper supply impacts

Copper has proven to be the most relevant metal among the modeled metals for future impact changes of low-carbon technologies. Therefore, we identify the variable which drives the copper MS scenarios. Figure 5 depicts how the impact of supplying 1 kg of copper through the global copper market changes due to different MS variables. MS scenarios primarily influence human toxicity and metal depletion impacts of technologies, so these are selected here. However, the overall pattern is very similar to the other categories, too (see Supporting Information S8, Figure C.4).

Variable 1, ore grade decline, is the only variable considerably increasing future impacts of up to 10–20% by 2050 for all categories. All other variables cause future impact reduction, with the exception of variable 3, energy-efficiency improvements, which has almost no effect in our model. This can be explained by the fact that the efficiency improvements are only applied to the primary production stage, smelting, and refining. However, the mining stage is of much higher energy intensity due to ore comminution (Azadi et al., 2020; Norgate & Jahanshahi, 2011). By and large, impact increases caused by variable 1 are more than counterbalanced by other variables with the result that the PMS developments, which are composed of variables 1–4, continuously lower future impacts. Figure 5 further reveals that the PMS trend is mostly dictated by variable 4, a decline of hydrometallurgical production shares (see discussion).

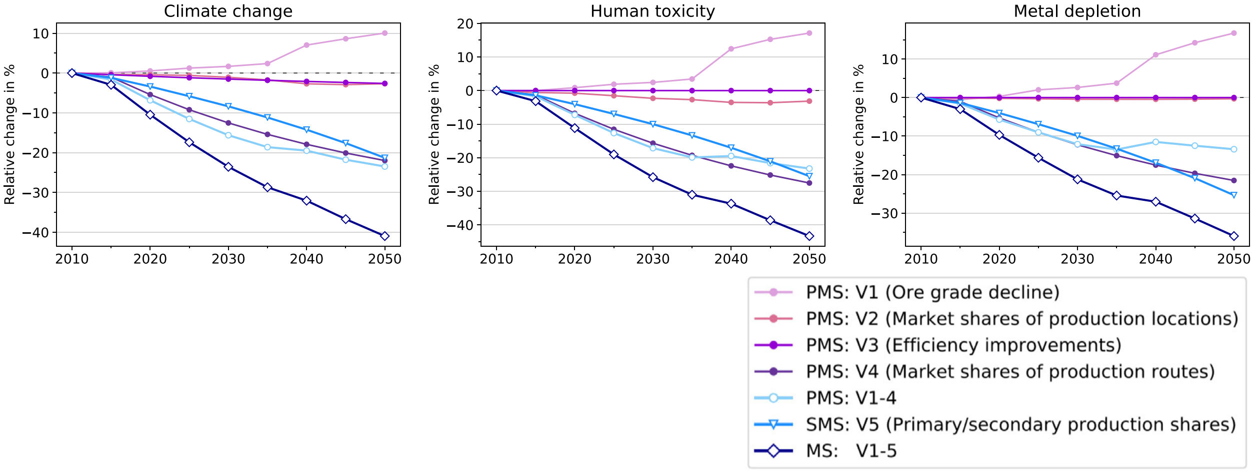


FIGURE 5 Prospective LCA results for the global market of copper: effect of variables 1 to 5
Prospective LCA results for the global market of copper supplying 1 kg of copper: effect of variables 1 to 5. Relative change refers to the impact of the scenario in the given year compared to the impact of 2010. No additional ES scenario is incorporated. For other impact categories see Supporting Information S8, Figure C.4. Underlying data used to create this figure can be found in Supporting Information S6. MS, metal supply; PMS, primary metal supply; SMS, secondary metal supply; V, variable

Thus, variables 4 and 5 drive the high reductions of future copper supply impacts. Therefore, among our variables, they represent the most effective ones to curtail future impacts of low-carbon technologies through MS changes.

4 | DISCUSSION

This study aimed to identify the trends and drivers of future environmental impacts of metal supply chains and their influence on low-carbon technologies. We jointly integrated metal and electricity scenarios (based on Mendoza Beltran et al. (2020)) into the ecoinvent 3.5 (cutoff version) database. The unique feature of this approach is that it takes into account the interconnected nature of these two sectors as described by the energy-resource nexus, since it maintains the network of supply chains in ecoinvent. Specifically, it ensures that "futurized" metal supply chains make use of future electricity and vice versa. Moreover, all other processes in these databases build upon the "futurized" metal and electricity supply chains, which makes the databases suitable for other prospective LCA applications.

Our results indicate that environmental impacts of both metal supplies and low-carbon technologies will decrease in the future per functional unit, that is, per kg metal or kWh energy, which is good news for the energy transition. However, this is not sufficient to offset increasing metal depletion impacts of a greener electricity mix. Of the modeled future metal supply changes, we found that increasing recycling shares (variable 5) is the most powerful to reduce future impacts associated with metal supply and can overcompensate increasing impacts due to ore grade decline (variable 1). Furthermore, we revealed that the share of hydrometallurgical copper production can affect future impacts of copper supply considerably. Moreover, this study has shown that MS and ES scenarios affect different impact categories: MS scenarios especially drive impact reductions of human toxicity and metal depletion, while ES scenarios highly reduce climate change impacts. Of all modeled metals, copper has the largest influence on the environmental impacts of low-carbon technologies.

The approach of integrating both metal and electricity supply scenarios into ecoinvent has proven effective to reveal interdependencies. For instance, only considering MS in isolation would either underestimate future impact reductions for categories of climate change, PMF, and POF (see Cu, Pb, Ni), or lead to wrong conclusions. The latter occurs, for example, for ferronickel and zinc, where considering only MS erroneously suggests increased impacts. On the other hand, solely including ES scenarios, as was done by Mendoza Beltran et al. (2020), underestimates potential future impact reductions in human toxicity and metal depletion. Our approach furthermore demonstrated the interacting effect of scenarios, that is, impact changes due to individual scenarios do not add up to the joint effect of simultaneously incorporated scenarios. This effect was also found by Mendoza Beltran et al. (2020).

These findings seem to be consistent with previous studies. A direct comparison with van der Voet et al. (2019) is only partly possible, due to differences, for example, in modeling approaches, assumed metal supply chains, ecoinvent versions, or choice of ES scenarios and impact categories (see Supporting Information S8, Section D.2). Our result that declining copper ore grades increase climate change impacts of copper supply by up to 20% is consistent with van der Voet et al. (2019). They also found that a strong electricity scenario can achieve considerable reductions for climate change impacts of metal supply, as well as that it can compensate increasing climate change impacts due to ore grade decline. Moreover, our results are in line with their findings that higher recycling shares can considerably decrease future impacts, and that increasing energy efficiency only has a small effect on primary copper production.

Furthermore, our findings are confirmed by Nuss and Eckelman (2014), who found that certain metal production impacts, such as, human toxicity, cannot be controlled by energy inputs, but are determined by emissions of toxic elements or treatment of sulfidic tailings resulting from mining activities.

Lastly, our finding that the production of copper is among the most important material supplies influencing impacts of low-carbon technologies (along with iron and aluminum) is confirmed by Hertwich et al. (2015). Moreover, they also stress the relevance of high toxicity impacts of copper mining caused by tailings and overburden material.

Overall, this study stresses the relevance of regulations for a greener electricity supply as well as increased metal recycling rates. Furthermore, the results show that renewable electricity might reduce impacts for climate change, but achieves little to no benefits for impacts of human toxicity, PMF, or POF. Thus, to lower these impacts from metal supply, regulations are required supporting the implementation of technology on a mine and refining plant level to curb emissions from, for example, tailings or smelter slags. Additional improvements could be achieved through a greener heat supply where applicable (see Supporting Information S8, Section C.3.1). To support such a transition toward more responsible metal supply and thereby lowering impacts from low-carbon technologies, sustainable sourcing of metals is key. This could be facilitated, for example, through certification systems for both metal and technology producers. To achieve impact reductions as fast as possible, copper production should be addressed first.

There are some important limitations associated with our study. Our findings describe relative impact changes, so impacts per kg or per kWh. Yet, the expected increase in global metal demand may still lead to rising global environmental impact from metal supply chains in the future (no absolute decoupling) (Elshkaki et al., 2018).

Given the complexity of metal supply chains (Northey et al., 2018), our MS models suffer from certain limitations regarding the factors considered and their accuracy. First, the effect of declining ore grades (variable 1) is based on an average global ore grade–energy relation instead of one specific for different production routes. Second, the modeling factor, $\delta_E(t)$, derived from this relation is applied as a proxy to all other in- and outflows of the mining process. Thus, we increased or decreased all inputs and outputs from the mining process by the same factor as a function of the ore grade, thus implicitly assuming that all parts of the mining process are affected by ore grade decline to the same degree as energy inputs (see Supporting Information S8, Section D.1, for a more detailed discussion). Further research is needed to identify more precise effects of ore grade decline on other parameters than energy, such as water consumption (Northey et al., 2013) or land use. Third, we assume that hydrometallurgical copper production shares will decrease from the current 19% to 8% in 2050 (variable 4), which is, although based on an analysis of recent trends, highly uncertain. Long-term production shares of hydrometallurgical copper production from oxide ores is expected to decline over time as shallow and highly accessible oxidised copper ores are gradually depleted. There is also potential for increases in the use of hydrometallurgy for extraction of copper from low-grade sulfide ores, particularly if large advances in bioleaching or in-situ leaching of copper sulfide ores are made. Moreover, the fact that impacts of hydrometallurgical copper production are higher compared to pyrometallurgical copper production in ecoinvent has to be interpreted very carefully, since other studies show that environmental impacts of hydrometallurgical copper production are lower than for pyrometallurgical production (Azadi et al., 2020; Norgate & Jahanshahi, 2010). In our model, hydrometallurgical copper production is represented via one process in ecoinvent. Such a global average cannot sufficiently represent the current diversity of industrial processes and site-specific conditions such as ore grades and ore types. Since this study focuses on future trends of impacts using background scenarios incorporated into ecoinvent, such as market share developments, improving the disputed data basis of hydrometallurgical processing is not within our scope. Figure 5 reveals, that the results of an overall decreasing trend for future impacts of copper and of the low-carbon technologies would not change, if variable 4, decreasing hydrometallurgical production, was kept constant, since increasing recycling shares is powerful enough to offset impact increases due to ore grade decline. More detailed, process-specific data is needed to more accurately determine the role of hydrometallurgical copper production for future impacts of copper supply.

Another limitation is that we did not include recycling (SMS scenarios, variable 5) for zinc and ferronickel due to (a) a lack of data for ferronickel in the scenarios of Elshkaki et al. (2018); and (b) the fact that zinc's secondary production projections show the lowest increase compared to all other metals within the scenarios of Elshkaki et al. (2018), that is, less than 5% from 8.1% in 2010 until 2050 (see Supporting Information S8, Figure B.18). In view of a transition toward a circular economy, it is essential to consider recycling scenarios in the future.

Furthermore, we applied regionalized scenarios only for copper for future ore grade decline and future shares of primary production locations (variable 1 and 2) since in ecoinvent 3.5 regionalized datasets were available only for copper. Future research should develop refined methods for regionalization of mining and metal production scenarios via incorporating region- and site-specific mining conditions, as well as industry production scheduling. Moreover, the model sophistication could be improved by adding more factors, such as chemical usages, recycling efficiencies, or treatment of tailings. Our result that copper has the largest influence on the environmental impacts of low-carbon technologies of all modeled metals could be biased, as more variables and more radical changes were modeled for copper than for the other metals (five variables for Cu, two for Ni and Pb, and only one for FeNi and Zn). Therefore, it is more likely for copper scenarios to achieve stronger effects than for other metals.

Another model shortcoming is the limited inclusion of technological innovation. We added new technologies to the ecoinvent database for the ES scenarios (carbon capture and storage, and concentrated solar power), but not for the MS scenarios. The MS scenarios have proven however that metal supply impacts vary considerably depending on the production routes (see hydrometallurgical and secondary production). Thus, further research could explore the potential influence of new technologies, such as, EVs in mining, novel recycling technologies, or pollution control technologies, and of low-carbon heat supply, for example, through green hydrogen.

Our approach of incorporating several scenarios simultaneously demonstrated the interacting effect of scenarios. This emphasizes the need for an integrated approach, that is, joint background adaptations, since evaluating scenarios separately instead of in combination fails to capture system-wide interactions.

So far, our study considers four metals. Thus, the completeness of prospective LCAs can be increased by adding supply scenarios for more metals, such as steel, aluminum, manganese (Hertwich et al., 2015; van der Voet et al., 2019), lithium (Mohr et al., 2012; Stamp et al., 2012), or cobalt (Tisserant & Pauliuk, 2016).

To gain more in-depth insights into the consequences of future metal supplies and emerging technologies, more impact categories need to be examined, such as ecotoxicity or land transformation (Gibon et al., 2017; Nuss & Eckelman, 2014). Additionally, the characterization methods for metal depletion have been highly debated (Berger et al., 2020; Brent & Hietkamp, 2006; Northey et al., 2018; Sonderegger et al., 2020). Greater insight may be possible through comparing results using multiple impact methods for this category.

Lastly, our scenarios may not always be fully consistent in relation to each other. As IMAGE does not offer scenarios for future metal supply, we generated these from other sources. We tried to achieve suitable matches, for instance, between the SMS Market-First and ES-BAU scenarios. Moreover, the MS variables are neither coupled to each other, nor to the ES scenarios. For our results this means that, for example, the effect of ES scenarios on metal depletion might have been underestimated, since the type of ES scenario does not influence our ore grade decline scenario. To ensure higher consistency, research is required on generating more integrated scenario models (Pauliuk et al., 2015a, 2015b).

For these reasons, the results presented in this paper should rather be seen as an indication of possible trends until more data and more sophisticated models can further reduce uncertainties.

With its scenario incorporation approach, this study contributes toward more consistent and reproducible modeling approaches of prospective LCAs. Our LCI databases and LCA results are completely reproducible with an ecoinvent license. For this, the Python code and metal scenarios are documented in Supporting Information S8 (Chapters A and B) and provided in a repository (Harpprecht et al., 2021). The needed data from IMAGE is available from PBL (PBL, 2019). Moreover, the MS scenario data can be used within the Activity Browser, a graphical user interface of Brightway (Steubing et al., 2020), also in combination with the IMAGE scenarios via a so-called superstructure approach (de Koning & Steubing, 2020; Steubing & de Koning, 2021).

Thus, our background scenarios can directly be used for prospective LCAs of any other technology, and can thereby help to better inform decision-makers in the ongoing effort to move toward a sustainable economy. Being transparently stored in excel files, the MS scenarios can furthermore easily be extended by other researchers. Although we demonstrate the scenario incorporation at the example of ecoinvent, similar approaches could be applied to other LCI databases.

5 | CONCLUSIONS

We modeled future metal supply (MS) scenarios for four metals: copper, nickel, zinc, and lead. The scenarios comprise five variables to estimate future developments in metal supplies until 2050: ore grade decline, primary production locations, energy-efficiency improvements, primary production routes, and shares of primary and secondary production. Furthermore, we added electricity supply (ES) scenarios which describe possible future energy systems.

Considering both metal and electricity supply scenarios, we investigated how environmental impacts of future metal supply, electricity supply, and low-carbon technologies will develop in the future via prospective LCAs, and examined the key drivers for those future impact changes. The distinctive feature of our approach is the concept of incorporating scenario data into an LCI database, namely ecoinvent. This means that ecoinvent processes are directly modified, so that changes become effective in the entire database, that is, future metal supply chains make use of future electricity and vice versa. Thereby, new background databases (representing models of a future economy) are created.

Based on our scenarios, we found that impacts of metal supply, electricity supply, and low-carbon technologies are likely to decrease per kg metal or kWh energy. Considering both metal and electricity scenarios has proven to be essential, since they drive impacts in different categories: improving metal supply can lower impacts of human toxicity and metal depletion, while a greener electricity supply can highly reduce climate change impacts. Moreover, we identified increasing recycling shares as the most powerful measure for limiting future metal supply impacts and for compensating impact increases caused by declining ore grades. Furthermore, it was revealed that impacts of low-carbon technologies due to metal supply could be reduced most effectively through improvements of copper supply. However, these improvements are far from sufficient to compensate increasing metal depletion impacts of a greener electricity mix which may almost double per kWh by 2050. It is important to stress that these scenarios are not predictions, but an analysis of possible future developments.

Overall, our integrated scenario incorporation succeeded not only in analyzing interlinked supply systems, as given by the energy-resource nexus, but also allowed to capture interactions between different scenarios. Calculating impacts of scenarios separately does not add up to their combined effect. Therefore, capturing the joint effect of a combination of scenarios is crucial, as modeling them in isolation can lead to incorrect conclusions.

With scenario data and Python code supplied in the Supporting Information, our future databases can easily be reproduced, extended with more scenarios, and used as background for other prospective LCAs. This study thus constitutes one step toward improved consistency of prospective LCAs, specifically regarding the evaluation of scenarios. However, evaluations strongly rely on the quality of the applied scenarios. Therefore, better scenarios are needed: scenarios that consider more factors, such as geographical or technological details, that cover more metal supply chains, and, ideally, are coupled to each other.

ACKNOWLEDGMENTS

The authors would like to thank Koen Kuipers and David Turner for sharing their knowledge on metal supply systems, Daniel de Koning for his support with Brightway2, as well as Brenda Miranda-Xicotencatl and Marc van der Meide for their feedback on the manuscript. The authors would like to express their gratitude to Angelica Mendoza Beltran and PBL who supplied the electricity and IMAGE scenario data. Lastly, the authors thank the reviewers for their helpful and insightful feedback.

FUNDING INFORMATION

No direct funding was received for this work.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Carina Harpprecht https://orcid.org/0000-0002-2878-0139
Lauran van Oers https://orcid.org/0000-0002-7383-604X
Stephen A. Northey https://orcid.org/0000-0001-9001-8842
Yongxiang Yang https://orcid.org/0000-0003-4584-6918
Bernhard Steubing https://orcid.org/0000-0002-1307-6376

REFERENCES

Alonso, E., Sherman, A. M., Wallington, T. J., Everson, M. P., Field, F. R., Roth, R., & Kirchain, R. E. (2012). Evaluating rare earth element availability: A case with revolutionary demand from clean technologies. *Environmental Science & Technology*, *46*(6), 3406–3414. https://doi.org/10.1021/es203518d

Arvesen, A., Luderer, G., Pehl, M., Bodirsky, B. L., & Hertwich, E. G. (2018). Deriving life cycle assessment coefficients for application in integrated assessment modelling. *Environmental Modelling & Software*, *99*, 111–125. https://doi.org/10.1016/j.envsoft.2017.09.010

Arvidsson, R., Tillman, A.-M., Sandén, B. A., Janssen, M., Nordelöf, A., Kushnir, D., & Molander, S. (2017). Environmental assessment of emerging technologies: Recommendations for prospective LCA. *Journal of Industrial Ecology*, *22*(6), 1286–1294. https://doi.org/10.1111/jiec.12690

Azadi, M., Northey, S. A., Ali, S. H., & Edraki, M. (2020). Transparency on greenhouse gas emissions from mining to enable climate change mitigation. *Nature Geoscience*, *13*(2), 100–104.

Bauer, C., Hofer, J., Althaus, H. J., Del Duce, A., & Simons, A. (2015). The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework. *Applied Energy*, *157*, 871–883. https://doi.org/10.1016/j.apenergy.2015.01.019

Berger, M., Sonderegger, T., Alvarenga, R., Bach, V., Cimprich, A., Dewulf, J., Frischknecht, R., Guinée, J., Helbig, C., Huppertz, T., Jolliet, O., Motoshita, M., Pena, A. A., Rugani, B., Sahnoune, A., Schrijvers, D., Schulze, R., Sonnemann, G., Valero, A., Weidema, B. P., & Young, S. B. (2020). Mineral resources in life cycle impact assessment: Part II–recommendations on application-dependent use of existing methods and on future method development needs. *The International Journal of Life Cycle Assessment*, *25*, 798–813. https://doi.org/10.1007/s11367-020-01737-5

Beylot, A., & Villeneuve, J. (2017). Accounting for the environmental impacts of sulfidic tailings storage in the life cycle assessment of copper production: A case study. *Journal of Cleaner Production*, *153*, 139–145. https://doi.org/10.1016/J.JCLEPRO.2017.03.129

Bleischwitz, R., Hoff, H., Spataru, C., van der Voet, E., & Van Deveer, S. D. (2017). *Routledge handbook of the resource nexus*. Routledge.

Brent, A., & Hietkamp, S. (2006). The impact of mineral resource depletion - In response to Steen BA (2006): Abiotic resource depletion: Different perceptions of the problem with mineral deposits. Int J LCA 11 (Special Issue 1) 49-54. *The International Journal of Life Cycle Assessment*, *11*(5), 361–362. https://doi.org/10.1065/lca2006.08.269

Bruckner, T., Bashmakov, I. A., Mulugetta, Y., Chum, H., de la Vega Navarro, A., Edmonds, J., Faaij, A., Fungtammasan, B., Garg, A., Hertwich, E., Honnery, D., Infield, D., Kainuma, M., Khennas, S., Kim, S., Nimir, H. B., Riahi, K., Strachan, N., Wiser, R., & Zhang, X. (2014). Energy systems. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* pages 5–1. Cambridge University Press.

COCHILCO. (2019). Forecast for electricity consumption in the copper mining industry, 2018–2029. https://doi.org/10.35624/jminer2019.01.05

Cox, B., Mutel, C. L., Bauer, C., Mendoza Beltran, A., & van Vuuren, D. P. (2018). Uncertain environmental footprint of current and future battery electric vehicles. *Environmental Science & Technology*, *52*(8), 4989–4995. https://doi.org/10.1021/acs.est.8b00261

Crowson, P. (2012). Some observations on copper yields and ore grades. *Resources Policy*, *37*(1), 59–72. https://doi.org/10.1016/J.RESOURPOL.2011.12.004

de Koning, A., Kleijn, R., Huppes, G., Sprecher, B., van Engelen, G., & Tukker, A. (2018). Metal supply constraints for a low-carbon economy? *Resources, Conservation and Recycling*, *129*, 202–208. https://doi.org/10.1016/J.RESCONREC.2017.10.040

de Koning, D., & Steubing, B. (2020). Brightway2 database superstructure repository. github.com/dgdekoning/brightway-superstructure

Deetman, S., Pauliuk, S., van Vuuren, D., van der Voet, E., & Tukker, A. (2018). Scenarios for demand growth of metals in electricity generation technologies, cars and electronic appliances. *Environmental Science & Technology*, *52*, 4950–4959. https://doi.org/10.1021/acs.est.7b05549

[dataset] Ecoinvent Centre. (2018). Ecoinvent database (version 3.5, allocation, cut-off by classification).

Elshkaki, A., Graedel, T. E., Ciacci, L., & Reck, B. (2016). Copper demand, supply, and associated energy use to 2050. *Global Environmental Change*, *39*, 305–315. https://doi.org/10.1016/j.gloenvcha.2016.06.006

Elshkaki, A., Graedel, T. E., Ciacci, L., & Reck, B. K. (2018). Resource demand scenarios for the major metals. *Environmental Science & Technology*, *52*(5), 2491–2497. https://doi.org/10.1021/acs.est.7b05154

Ericsson, M., Drielsma, J., Humphreys, D., Storm, P., & Weihed, P. (2019). Why current assessments of 'future efforts' are no basis for establishing policies on material use-a response to research on ore grades. *Mineral Economics*, *32*(1), 111–121. https://doi.org/10.1007/s13563-019-00175-6

Fizaine, F., & Court, V. (2015). Renewable electricity producing technologies and metal depletion: A sensitivity analysis using the EROI. *Ecological Economics*, *110*, 106–118. https://doi.org/10.1016/j.ecolecon.2014.12.001

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D. L., Obersteiner, M., Pachauri, S., Rao, S., Schmid, E., Schoepp, W., & Riahi, K. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, *42*, 251–267. https://doi.org/10.1016/J.GLOENVCHA.2016.06.004

Gibon, T., Arvesen, A., & Hertwich, E. G. (2017). Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. *Renewable and Sustainable Energy Reviews*, 1283–1290. https://doi.org/10.1016/j.rser.2017.03.078

Gibon, T., Wood, R., Arvesen, A., Bergesen, J. D., Suh, S., & Hertwich, E. G. (2015). A methodology for integrated, multiregional life cycle assessment scenarios under large-scale Technological change. *Environmental Science & Technology*, *49*(18), 11218–11226. https://doi.org/10.1021/acs.est.5b01558

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. (2013). *ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level First edition (version 1.08) Report I: Characterisation*. Ministry of Housing, Spatial Planning and Environment (VROM), The Netherlands.

Graedel, T. E., & van der Voet, E. (Eds.) (2010). Linkages of sustainability. The MIT Press, Cambridge.

Harpprecht, C., van Oers, L., Northey, S. A., Yang, Y. & Steubing, B. (2021). Scenario data for article: Environmental impacts of key metals' supply and low-carbon technologies are likely to decrease in the future (version1). [dataset] https://doi.org/10.5281/zenodo.4785135

Hertwich, E., Gibon, T., Bouman, E. A., Arvesen, A., Suh, S., Heath, G. A., Bergesen, J. D., Ramirez, A., Vega, M. I., & Shi, L. (2015). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(20), 6277–82.

IEA. (2012). World energy outlook 2012. IEA, International Energy Agency.

International Copper Study Group. (2018). ICSG 2018 statistical yearbook. International Copper Study Group.

IPCC (2014). Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781107415324

ISO 14040. (2006). Environmental management – Life cycle assessment – Principles and framework. International Organisation for Standardisation (ISO).

Kleijn, R., van der Voet, E., Kramer, G. J., van Oers, L., & van der Giesen, C. (2011). Metal requirements of low-carbon power generation. *Energy*, *36*(9), 5640–5648. https://doi.org/10.1016/J.ENERGY.2011.07.003

Kuipers, K. J., van Oers, L. F., Verboon, M., & van der Voet, E. (2018). Assessing environmental implications associated with global copper demand and supply scenarios from 2010 to 2050. *Global Environmental Change*, 106–115. https://doi.org/10.1016/j.gloenvcha.2018.02.008

Kulczycka, J., Lelek, u., Lewandowska, A., Wirth, H., & Bergesen, J. D. (2016). Environmental impacts of energy-efficient pyrometallurgical copper smelting technologies: The consequences of technological changes from 2010 to 2050. *Journal of Industrial Ecology*, *20*(2), 304–316. https://doi.org/10.1111/jiec.12369

Le Blanc, D. (2015). Towards integration at last? The sustainable development goals as a network of targets. *Sustainable Development*, *23*(3), 176–187. https://doi.org/10.1002/sd.1582

Lesage, P. (2019). Presamples repository. https://github.com/PascalLesage/presamples

Lesage, P., Mutel, C., Schenker, U., & Margni, M. (2018). Uncertainty analysis in LCA using precalculated aggregated datasets. *International Journal of Life Cycle Assessment*, *23*(11), 2248–2265. https://doi.org/10.1007/s11367-018-1444-x

Mendoza Beltran, A., Cox, B., Mutel, C., van Vuuren, D. P., Font Vivanco, D., Deetman, S., Edelenbosch, O. Y., Guinée, J., & Tukker, A. (2020). When the background matters: Using scenarios from integrated assessment models in prospective life cycle assessment. *Journal of Industrial Ecology*, *24*, 64–79. https://doi.org/10.1111/jiec.12825

Mohr, S. (2010). *Projection of world fossil fuel production with supply and demand interactions*. PhD thesis, The University of Newcastle.

Mohr, S. H., Mudd, G. M., & Giurco, D. (2012). Lithium resources and production: Critical assessment and global projections. *Minerals*, *2*(1), 65–84. https://doi.org/10.3390/min2010065

Mudd, G. M. (2010). The environmental sustainability of mining in Australia: Key mega-trends and looming constraints. *Resources Policy*, *35*, 98–115. https://doi.org/10.1016/j.resourpol.2009.12.001

Mudd, G. M., & Jowitt, S. M. (2014). A detailed assessment of global nickel resource trends and endowments. *Economic Geology*, *109*(7), 1813–1841.

Mudd, G. M., & Jowitt, S. M. (2018). Growing global copper resources, reserves and production: Discovery is not the only control on supply. *Economic Geology*, *113*(6), 1235–1267. https://doi.org/10.5382/econgeo.2018.4590

Mudd, G. M., Jowitt, S. M., & Werner, T. T. (2017). The world's lead-zinc mineral resources: Scarcity, data, issues and opportunities. *Ore Geology Reviews*, *80*, 1160–1190.

Mutel, C. (2017a). Brightway: An open source framework for life cycle assessment. *The Journal of Open Source Software*, *2*(12). https://doi.org/10.21105/joss.00236

Mutel, C. (2017b). Wurst documentation. https://wurst.readthedocs.io/index.html

Mutel, C. (2018). Brightway2: Advanced life cycle assessment framework. https://brightwaylca.org/

Mutel, C., & Vandepaer, L. (2019). Wurst examples repository. https://github.com/IndEcol/wurstexamples

Nordelöf, A., Messagie, M., Tillman, A.-M., Ljunggren Söderman, M., Van Mierlo, J., Van Mierlo, J., Messagie, M., & Ljunggren Söderman, M. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles-what can we learn from life cycle assessment? *International Journal of Life Cycle Assessment*, *19*, 1866–1890. https://doi.org/10.1007/s11367-014-0788-0

Norgate, T., & Haque, N. (2010). Energy and greenhouse gas impacts of mining and mineral processing operations. *Journal of Cleaner Production*, *18*(3), 266–274. https://doi.org/10.1016/j.jclepro.2009.09.020

Norgate, T., & Jahanshahi, S. (2006). Energy and greenhouse gas implications of deteriorating quality ore reserves. Melbourne.

Norgate, T., & Jahanshahi, S. (2010). Low grade ores - Smelt, leach or concentrate? *Minerals Engineering*, *23*(2), 65–73. https://doi.org/10.1016/j.mineng.2009.10.002

Norgate, T., & Jahanshahi, S. (2011). Reducing the greenhouse gas footprint of primary metal production: Where should the focus be? *Minerals Engineering*, *24*(14), 1563–1570. https://doi.org/10.1016/j.mineng.2011.08.007

Norgate, T., & Rankin, W. J. (2000). Life cycle assessment of copper and nickel production. In *International Conference on Minerals Processing and Extractive Metallurgy* (pp. 133–138). Australian Institute of Mining and Metallurgy.

Northey, S. A., Haque, N., & Mudd, G. (2013). Using sustainability reporting to assess the environmental footprint of copper mining. *Journal of Cleaner Production*, *40*, 118–128. https://doi.org/10.1016/j.jclepro.2012.09.027

Northey, S. A., Mohr, S., Mudd, G. M., Weng, Z., & Giurco, D. (2014). Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. *Resources, Conservation and Recycling*, *83*, 190–201. https://doi.org/10.1016/j.resconrec.2013.10.005

Northey, S. A., Mudd, G. M., & Werner, T. T. (2018). Unresolved complexity in assessments of mineral resource depletion and availability. *Natural Resources Research*, *27*(2), 241–255. https://doi.org/10.1007/s11053-017-9352-5

Nuss, P., & Eckelman, M. J. (2014). Life cycle assessment of metals: A scientific synthesis. *PLoS ONE*, *9*(7), e101298. https://doi.org/10.1371/journal.pone.0101298

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., Mathur, R., & van Vuuren, D. P. (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, *122*(3), 387–400. https://doi.org/10.1007/s10584-013-0905-2

Paraskevas, D., Kellens, K., Van De Voorde, A., Dewulf, W., & Duflou, J. R. (2016). Environmental impact analysis of primary aluminium production at country level. *Procedia CIRP*, *40*, 209–213. https://doi.org/10.1016/j.procir.2016.01.104

Pauliuk, S., Majeau-Bettez, G., & Müller, D. B. (2015a). A general system structure and accounting framework for socioeconomic metabolism. *Journal of Industrial Ecology*, *19*(5), 728–741. https://doi.org/10.1111/jiec.12306

Pauliuk, S., Majeau-Bettez, G., Mutel, C. L., Steubing, B., & Stadler, K. (2015b). Lifting industrial ecology modeling to a new level of quality and transparency: A call for more transparent publications and a collaborative open source software framework. *Journal of Industrial Ecology*, *19*(6), 937–949. https://doi.org/10.1111/jiec.12316

PBL. (2019). IMAGE integrated model to assess the global environment. Download. https://models.pbl.nl/image/index.php/Downloadpackages

Pesonen, H.-L., Ekvall, T., Fleischer, G., Jahn, C., Klos, Z. S., Rebitzer, G., Sonnemann, G. W., Tintinelli, A., Weidema, B. P., WenzeF, H., & Weidema, B. (2000). Framework for Scenario Development in LCA. *International Journal of Life Cycle Assessment*, *5*(1), 21–30.

Rankin, W. J. (2011). *Minerals, metals and sustainability: Meeting future material needs*. CSIRO publishing.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., & Tavoni, M. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. https://doi.org/10.1016/J.GLOENVCHA.2016.05.009

Roelich, K., Dawson, D. A., Purnell, P., Knoeri, C., Revell, R., Busch, J., & Steinberger, J. K. (2014). Assessing the dynamic material criticality of infrastructure transitions: A case of low carbon electricity. *Applied Energy*, *123*, 378–386. https://doi.org/10.1016/j.apenergy.2014.01.052

Rötzer, N., & Schmidt, M. (2020). Historical, current, and future energy demand from global copper production and its impact on climate change. *Resources*, *9*(4), 44. https://doi.org/10.3390/resources9040044

Sandén, B. A. (2007). Standing the test of time: Signals and noise from environmental assessments of energy technologies. *MRS Proceedings*, *1041*, 05–06. https://doi.org/10.1557/PROC-1041-R05-06

Sonderegger, T., Berger, M., Alvarenga, R., Bach, V., Cimprich, A., Dewulf, J., Frischknecht, R., Guinée, J., Helbig, C., Huppertz, T. et al. (2020). Mineral resources in life cycle impact assessment-part I: a critical review of existing methods. *The International Journal of Life Cycle Assessment*, *25*, 784–797. https://doi.org/10.1007/s11367-020-01736-6

Stamp, A., Lang, D. J., & Wäger, P. A. (2012). Environmental impacts of a transition toward e-mobility: The present and future role of lithium carbonate production. *Journal of Cleaner Production*, *23*(1), 104–112. https://doi.org/10.1016/j.jclepro.2011.10.026

Stehfest, E., van Vuuren, D., Kram, T., Bouwma, L., Alkemade, R., Bakkenes, M., Biemans, H., & Al, E. (2014). Integrated assessment of global environmental change with IMAGE 3.0 model description and policy applications. The Hague: PBL Netherlands Environmental Assessment Agency.

Steubing, B., de Koning, D., Haas, A., & Mutel, C. L. (2020). The activity browser-An open source LCA software building on top of the brightway framework. *Software Impacts*, *3*.

Steubing, B., & de Koning, D. G. (2021). Making the use of scenarios in LCA easier: The superstructure approach. *International Journal of Life Cycle Assessment*. Manuscript submitted for publication.

Tisserant, A., & Pauliuk, S. (2016). Matching global cobalt demand under different scenarios for co-production and mining attractiveness. *Journal of Economic Structures*, *4*. https://doi.org/10.1186/s40008-016-0035-x

Tokimatsu, K., Höök, M., McLellan, B., Wachtmeister, H., Murakami, S., Yasuoka, R., & Nishio, M. (2018). Energy modeling approach to the global energy-mineral nexus: Exploring metal requirements and the well-below 2 °C target with 100 percent renewable energy. *Applied Energy*, 1158–1175. https://doi.org/10.1016/j.apenergy.2018.05.047

UNEP (United Nations Environment Programme). (2007). *Global Environment Outlook GEO-4: Environment for development. United Nations Environment Programme, Nairobi, Kenya*. UNEP. https://doi.org/10.1227/01.NEU.0000108643.94730.21

UNEP (United Nations Environment Programme). (2013). Environmental risks and challenges of anthropogenic metals flows and cycles, a report of the working group on the global metal flows to the international resource panel. Van der Voet, E.; Salminen, R.; Eckelman, M.; Mudd, G.; Norgate, T.; Hischier, R.

Valero, A., Valero, A., & Domínguez, A. (2011). Trends of exergy costs and ore grade in global mining. In *Proceedings of SDIMI 2011. Sustainable Development in the Minerals Industry, Aachen, Germany*, pp. 301–316.

van der Voet, E., van Oers, L., Verboon, M., & Kuipers, K. (2019). Environmental implications of future demand scenarios for metals: Methodology and application to the case of seven major metals. *Journal of Industrial Ecology*, *23*(1), 141–155. https://doi.org/10.1111/jiec.12722

van Vuuren, D. P., Stehfest, E., Gernaat, D. E., Doelman, J. C., van den Berg, M., Harmsen, M., de Boer, H. S., Bouwman, L. F., Daioglou, V., Edelenbosch, O. Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P. L., van Meijl, H., Müller, C., van Ruijven, B. J., van der Sluis, S., & Tabeau, A. (2017). Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, *42*, 237–250. https://doi.org/10.1016/j.gloenvcha.2016.05.008

Vandepaer, L., & Gibon, T. (2018). The integration of energy scenarios into LCA: LCM2017 Conference Workshop, Luxembourg, September 5, 2017. *International Journal of Life Cycle Assessment*, *23*, 970–977. https://doi.org/10.1007/s11367-017-1435-3

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

West, J. (2011). Decreasing metal ore grades: Are they really being driven by the depletion of high-grade deposits? *Journal of Industrial Ecology*, *15*(2), 165–168. https://doi.org/10.1111/j.1530-9290.2011.00334.x

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Harpprecht C, van Oers L, Northey SA, Yang Y, Steubing B. Environmental impacts of key metals' supply and low-carbon technologies are likely to decrease in the future. *J Ind Ecol*. 2021;*25*:1543–1559. https://doi.org/10.1111/jiec.13181