2 Future environmental impacts of metals: A systematic review of impact trends, modelling approaches, and challenges

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Abstract

With the energy transition, the future demand for many metals is expected to sharply increase. We systematically reviewed studies which assessed future environmental impacts of metal supply chains. We evaluated their results regarding future impact trends, and their methods, i.e., modelling approaches, scenario variables, and data sources.

Our review yielded 40 publications covering 15 metals: copper, iron, aluminium, nickel, zinc, lead, cobalt, lithium, gold, manganese, neodymium, dysprosium, praseodymium, terbium, and titanium. Metals crucial for the energy transition, e.g., lithium or neodymium, are rarely addressed, unlike major metals. Results for future environmental impacts of metals strongly depend on scenario narratives and assumptions. We found that specific impacts (per kg) may decrease driven by, e.g., greener electricity, higher recycling shares, or novel technologies. Nevertheless, this is probably insufficient to compensate for surging demand. Thus, demand-related impacts are still likely to increase. We identified 15 scenario variables. The most common variables are background electricity mix, ore grade, recycling shares, demand, and energy efficiency.

It is crucial to better understand future impacts of more metals, considering also rising demand and impacts beyond GHG emissions. We recommend improving research practices towards open and collaborative research, to enable more harmonized, reusable and accurate scenario assessments.

2.1. Introduction

Metal production is not only energy-intensive and an important source of greenhouse gas (GHG) emissions, but also causes severe environmental impacts, such as land and water use, toxicity, ecosystem degradation and biodiversity loss (IRP, 2020a; Northey et al., 2016; Segura-Salazar and Tavares, 2018; Sonter et al., 2020; UNEP, 2013). Metal supply is responsible for ca. 10-17% of global GHG emissions and 12% of health impacts from particulate matter (Schenker et al., 2022; IRP, 2019). From 2000-2015, these impacts doubled, and toxicity impacts increased by about 50%, which can be partly attributed to an increasing metal ore extraction of ca. 2.7%/year (IRP, 2019). For GHGs, the by far largest contributor is iron and steel production causing about 71%, followed by aluminium (11%), calcium (8.8%), copper (1.6%), gold (1.2%), titanium (1.2%) and zinc (1.1%) (Nuss and Eckelman, 2014).

Given a growing population and the need for metal-intensive low-carbon technologies, e.g., for the energy transition, metal demand is expected to further rise in the future (Kleijn et al., 2011; Liang et al., 2022). This is not only the case for most major metals[1], like iron, aluminium or copper (Elshkaki et al., 2018; Watari et al., 2021), but also for minor or critical metals[2], such as neodymium, lithium, or cobalt (de Koning et al., 2018; Schlichenmaier and Naegler, 2022). Unless drastic measures are taken, environmental impacts caused by metal production may thus further increase (van der Voet et al., 2019).

Future developments of metal supply and their associated environmental impacts are complex and uncertain but need to be investigated to minimize future impacts of our society and to comply with climate and other environmental targets, e.g., the Paris Agreement or the Sustainable Development Goals (UN, 2015; 2019; IRP, 2020b). Due to the complexity of metal supply chains, a variety of factors may influence associated environmental impacts. Surging demand may lead to technological innovations and opening of new mining and production sites, or to lower recycling shares. Climate goals require adapting existing production facilities, e.g., via electrification (Lechtenböhmer et al., 2016) or carbon capture and storage (CCS) technologies (Chisalita et al., 2019). Further, they will lead to a decarbonized electricity supply in the future. Technologies may become more efficient due to learning effects related to higher production levels. Environmental factors, e.g., ore reserves and their quality, determine mined ore grades and overall production efficiency (Norgate and Haque, 2010).

Life Cycle Assessment (LCA) (ISO, 2006), specifically prospective LCA, is a powerful method to assess future environmental impacts of a product considering different scenarios and variables (van der Giesen et al., 2020). Metal supply chains contribute considerably to impacts of product systems (Reinhard et al., 2019). Therefore, it is essential to consider possible future developments in metal supply when assessing potential future impacts of other products or technologies (Harpprecht et al., 2021).

[1] Major metals are produced in very large quantities (Chen and Graedel, 2012; Elshkaki et al., 2018; van der Voet et al., 2019). For a detailed distinction of major, minor and critical metals, please refer to supplementary information, section S0.

[2] Minor metals are produced in small quantities, typically as by-products, and are partly considered critical (van Nielen et al., 2022; Nassar et al., 2015; Schrijvers et al., 2020) (see S0).

Various studies exist that assess future impacts of one or multiple metals, but their research scopes, scenario variables, and methodological choices are highly diverse, which potentially leads to different or even divergent conclusions. For instance, Wang et al. (2021) and van der Voet et al. (2019) report opposing results for future GHG emissions of global steel supply.

The differences in research scopes concerns, for example:

i) **geographical scopes** (e.g., the globe[3], the EU[4], China[5], the US[6], Australia[7]);

ii) **temporal scopes** (e.g., different temporal resolutions or scenario end years);

iii) **system boundaries and technological scopes** (e.g., the full metal supply chain, i.e., a metal market, including recycling[8] versus individual processes, like mining[9] or emerging technologies[10]);

iv) **the scale of impact assessment,** i.e., specific impacts (per kg) (Harpprecht et al., 2021) versus demand-related impacts (e.g., of global metal demand, as in van der Voet et al., 2019).

Additionally, the selection of scenario variables considered can greatly differ, ranging from, e.g., ore grades (van der Voet et al., 2019), emerging refining technologies (Chisalita et al., 2019), recycling shares (Ryberg et al., 2018) to background electricity scenarios (Sacchi et al., 2022). For the same scenario variable, studies may differ in:

i) **scenario modelling approaches**, i.e., the methods used to estimate future developments of a variable (e.g., extrapolation of historic trends (van der Voet et al., 2019) or using scenarios from integrated assessment models (IAMs) (Sacchi et al., 2022) or other models (Wang et al., 2021)); and

ii) **data sources** used for scenario variables (e.g., using scenario data from different scientific publications or models). For example, van der Voet et al. (2019) and Wang et al. (2021) both assess energy efficiency improvements for future steel production. Yet, van der Voet et al. (2019) extrapolate historic trends from steel statistics (WSA, 2016), while Wang et al. (2021) use multiple trends published by the international energy agency (IEA) (IEA, 2020).

Consequently, information about future environmental impacts of metals is available, but in a fragmented manner. While comprehensive overviews of current environmental impacts of metal production exist (Nuss and Eckelman, 2014; UNEP, 2013), they are lacking for future impacts. Research to date has not yet systematically compared the existing metal scenario studies. It is thus unknown whether consensus exists about the trends and driving factors of environmental impacts of future metal supply.

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[3] Ambrose and Kendall (2020); Langkau and Erdmann (2021); van der Meide et al. (2022); Wang et al. (2021); Watari et al. (2022).
[4] Ciacci et al. (2020); Koroma et al. (2020).
[5] Dong et al. (2020); Li et al. (2021).
[6] Farjana et al. (2019).
[7] Memary et al. (2012); Tan and Khoo (2005).
[8] van der Voet et al. (2019); Harpprecht et al. (2021); van der Meide et al. (2022).
[9] Kumar Katta et al. (2020); Song et al. (2017).
[10] Chisalita et al. (2019); Li et al. (2022).

Here, we aim to provide a systematic overview of previous studies about future environmental impacts of metals as well as of their scenario modelling approaches and data sources. We aim at answering two research questions:

1. *Which metals have been addressed by prior prospective LCA studies and what are expected future impact trends as well as the main drivers of these impacts?*
2. *What are the studied variables of the metal supply chains, the applied scenario modelling approaches, as well as data sources used?*

Based on the results of this study, we identify challenges and provide recommendations for assessments of future impacts of metals and how the sharing of scenario data within the LCA community can be improved. Moreover, the overview of variables, scenario modelling approaches and data sources serves as a source of information for LCA practitioners to support and accelerate their future research.

2.2. Methods

2.2.1. Literature search

We performed a systematic review following the PRISMA2020 statement (Henriksson et al., 2021; Page et al., 2021). PRISMA2020 stands for Preferred Reporting Items for Systematic reviews and Meta-Analyses. It provides guidance to enhance the transparency, completeness and accuracy of systematic reviews. We used the domain-specific interpretation guidance of STARR-LCA, the Standardized Technique for Assessing and Reporting Reviews of Life Cycle Assessment Data (STARR-LCA, Zumsteg et al., 2012), to complete the PRISMA 2020 checklist, provided in the SI (Tables S1.1-S1.3).

Search methods

The use of various methods for literature searches increases the comprehensiveness of systematic reviews (Mayo-Wilson et al., 2018; Xiao and Watson, 2019).

In this review, scientific literature available by 6/12/2021 was collected using two search queries and three search engines (Fig. 1). Since the search queries lead to over 90 results per engine, we continued with title screening for only the most relevant results according to the algorithm of each search engine:

1. Main search query:
   - Keywords: ((metal production) OR (metal AND mining)) AND LCA AND (future OR prospective)
   - Search engines: Leiden Catalogue[11] (top 50 results), Web of Science (top 50 results), Google Scholar (top 40 results)
2. Secondary search query:
   - Keywords: ((metal production) OR (metal AND mining)) AND energy AND (future OR prospective)
   - Search engine: Leiden Catalogue (top 50 results)

[11] https://catalogue.leidenuniv.nl

Additionally, we performed forward snowballing, using the relevance sorting engine of ResearchRabbit[12] to find articles connected to those already collected (Cole and Boutet, 2023; Matthews, 2021). For the snowballing, 20 seed papers were chosen based on the knowledge and expertise of the authors. Likewise, nine papers matching our intended scope were added from personal collections of the authors.

After removal of duplicates, this yielded a total of 139 papers as input for abstract screening. Each search method is further detailed in the SI (section S1.3).

Screening

To be selected, a publication had to meet all three inclusion criteria (see Fig. 1):

1. **metal production:** either mining, refining or further processing, or a combination of the three.
2. **environmental impacts:** CO_2 emissions or other environmental impacts are calculated from a life cycle perspective. Hence, review papers were excluded. For iron and steel, the calculation of GHG emissions was required to limit the number of studies to a reasonable amount.
3. **future developments, scenarios or variables:** the study should estimate future environmental impacts. Studies investigating emerging technologies were included as these are potential future alternatives for incumbent technologies. Studies that provide a parametrised model of current technology were also included, for example Manjong et al. (2021).

The geographical scope was not considered a criterion, so studies on a single country were included.

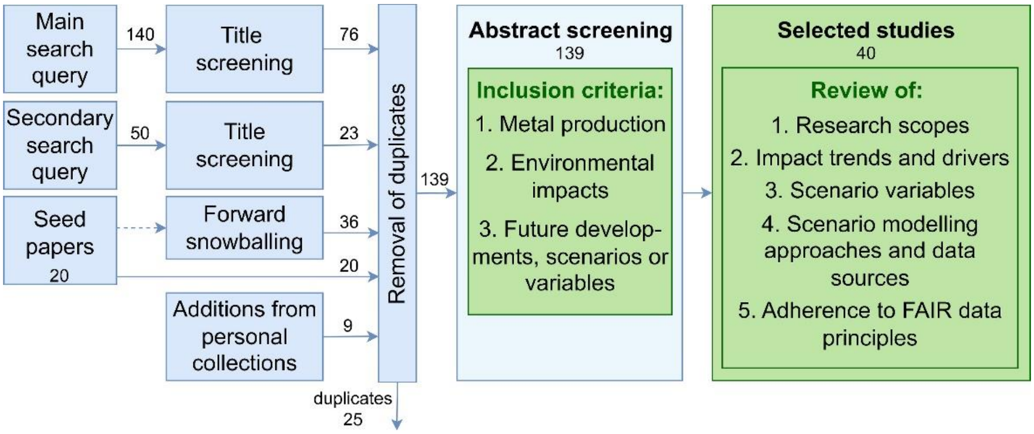


Fig. 1: Overview of the applied approach for the literature search. The abstract screening is documented in Harpprecht et al. (2023), Tables B.1, B2. FAIR: findable, accessible, interoperable and reusable.

[12] https://www.researchrabbit.ai/

2.2.2. Assessment of research scopes

We analysed the goal and scope of the selected papers regarding their:

- coverage of metals,
- geographical scopes,
- temporal scopes,
- scenario types,
- technological scopes.

Definitions are provided in Table 1.

2.2.3. Assessment of impact trends

To answer research question 1, we analysed the quantitative results of the selected papers, specifically their statements about how the environmental impacts of the studied metal(s) are expected to develop in the future. A direct comparison of impact results from different LCA studies is not possible without previous harmonization of all the LCA models (Zumsteg et al., 2012). Hence, we focus on trends rather than on the actual values.

For each metal, we categorized the reported impact trends with the help of four mutually exclusive indicators, which describe the direction of the expected trend of impacts from the base year to the future target year of the studies:

- “increase”, “equal”, and “decrease”;
- “direction depends on scenario”: the trend direction depends on the scenario and differs among the scenarios.

For a more detailed analysis presented in the supplement, we used two additional categories:

- “not clear”: the trend is in principle considered in the study but not clearly stated or shown;
- “not calculated”: the impact trend is not in the scope of the study.

This trend analysis was conducted for demand-related impacts (per annual metal demand) and specific impacts (per kg metal produced) (see definitions in Table 1). Further, we distinguished between impact trends of primary production and of the market (primary and secondary production) (see Table 1).

Finally, we identified major drivers for the change in future environmental impacts as reported by each study.

Please note that publications which do not quantitatively determine impacts are excluded in this analysis (see Table B.5 in Harpprecht et al. (2023)).

Table 1: Definition of terms used in this study.

Term	Definition	Sections
Scenario type	Classifies the approach to define plausible future situations according to their intended conditions: predictive (probable), normative (preferable) or explorative (possible). We further distinguish between explorative pathways (describing evolutions from present to future conditions) and explorative technology comparison (static snapshots comparing technology alternatives) (Bisinella et al., 2021; Börjeson et al., 2006; Pesonen et al., 2000).	2.2.2; 2.3.1
Technological scope	Defines the types of assessed technologies: emerging technology, dominant technology, or both.	
Specific impact	Environmental impact of supplying 1 kg of metal within the geographic scope of the reviewed paper.	2.2.3; 2.3.2
Demand-related impact	Environmental impact of the annual demand for a metal within the geographical scope of the reviewed paper, e.g., for a country or at global scale	
Primary production	Producing a metal from mined metal ores.	
Secondary production	Producing a metal through recycling, e.g., of metal scrap.	
Market	Market mix of metal supply from primary and secondary sources.	
Scenario variable	A property within the system of the metal supply chain or a factor outside of that system which is likely to change in the future and which may thereby influence the environmental performance of metal supply. Examples: ore grade; recycling share; background electricity mix, etc.	2.2.4; 2.3.3
Scenario modelling approach	The concept used to estimate how a scenario variable may develop in the future. Examples of categories: what-if scenarios; extrapolation of historic trends; taking the scenario from another model (e.g., an IAM); dynamic material flow analysis	2.2.5; 2.3.4
Data sources	The data sources used to model a scenario variable or representing input data for a model. Examples of categories: scientific publications; scenarios from IAMs; governmental data.	

2.2.4. Evaluation of scenario variables

The selected papers were screened to identify the scenario variables they used to model future environmental impacts of metal supply. A variable is defined as a property within the system of the metal supply chain or a factor outside of that system (e.g., the background electricity system) which is likely to change in the future and which may thereby influence the environmental performance of metal supply (see Table 1). The identified variables are then grouped into variable categories which are aligned to the stages of metal supply chains: 1) background (upstream processes, such as energy supply or other inputs to metal production); 2) mining; 3) processing & refining; 4) metal markets (e.g., recycling shares or demand) and 5) energy use (general for the metal supply chain, e.g., energy efficiency). Note that we qualitatively analyse the choice of scenario variables without a quantitative assessment of the effect of scenario variables, as this would require a prior harmonization of models (Zumsteg et al., 2012).

2.2.5. Evaluation of scenario modelling approaches and data sources

For each study, we identified the scenario modelling approach and the data sources used of each variable. Scenario modelling approach refers to the concept used to estimate how a variable may develop in the future (see Table 1).

For variables which appeared in more than 10 publications, we analysed the modelling approach and data sources in detail. For each of these variables, we categorized the used modelling approaches and data sources to identify patterns, common features or sources. A category was created, if it appeared more than once within a variable, otherwise it was classified as "other". Examples of categories are provided in Table 1.

2.2.6. Adherence to FAIR data principles

In the last step, we investigated the disclosure of life cycle inventory (LCI) and scenario data for the selected studies.

The FAIR data principles state that "all research objects should be Findable, Accessible, Interoperable and Reusable (FAIR) both for machines and for people" (Wilkinson et al., 2016, p. 3). FAIR data is important in the field of LCA (Hertwich et al., 2018), as data collection is very time consuming (Ghose, 2024). Thus, achieving a system where LCA data and scenario data is FAIR can have considerable time benefits. Ghose (2024) argues that storing LCA data in generic repositories such as Zenodo maximizes FAIRness of data sharing.

Firstly, we determined whether parts of the LCI data and scenario data were published or not at all disclosed. Secondly, we screened the publications for their compliance with FAIR data principles. The screening was conducted via a keyword search for common keywords like: FAIR data; machine readable; interop*; reus*; reproduc*; complete model; python; repository; zenodo; github; superstructure (for a complete list, see Table B.3 in Harpprecht et al. (2023)). Yields were screened again to remove false positives.

Lastly, we analysed the mentioning and choice of background databases in the reviewed studies.

2.3. Results

2.3.1. Research scopes of reviewed papers

The literature search and screening yielded 40 publications, which address 15 different metals (see Fig. 2.a). The identified studies were on early access or published between 2005 and 2021 (see Table S1.3). Copper was covered by the most studies followed by other major metals (iron and steel, Al, Ni, Zn, and Pb) (see Fig. 2.a). Future environmental impacts of minor metals (or ’technology metals', such as Co, Li and rare earth elements (REEs)) are currently rarely addressed (1-2 studies). In contrast, more studies assess the future demand of minor metals but neglect future environmental impacts (e.g., Elshkaki, 2021, 2020; Elshkaki and Graedel, 2015; Fu et al., 2020; Heijlen et al., 2021; Nguyen et al., 2021; Sverdrup and Ragnarsdottir, 2016; Tisserant and Pauliuk, 2016; Watari et al., 2019). These studies purely on future demand were excluded.

Comparing the identified 15 metals (Fig. 2.a) with the 15 metals of the highest GHG emissions for global primary production in 2008 (Nuss and Eckelman, 2014), studies are lacking for calcium, magnesium, chromium, boron, selenium, and silver. For ecosystem damage and human health, the lack applies to molybdenum, mercury, uranium, platinum and antimony.

The geographic scope is mostly global (19 studies), whereas others focus on a specific country (see Fig 2.b). For the temporal scope, most studies start the analysis at present, although a specific year is not always specified. As end year, a common choice is 2050, along with some other rounded years. Several studies do not report a specific end year but call it “future”.

Most studies (85%) have chosen an explorative approach as scenario type. They either investigate pathways (55%, 22 studies), i.e., dynamic developments over several years (e.g., from 2020 to 2050), or make an explorative technology comparison (30%, 12 studies). Technology comparisons are static and compare two or more metal production methods under future conditions (e.g., in 2050). Various kinds of pathways were encountered, such as different socio-economic storylines (e.g., IEA, 2017; Riahi et al., 2017) or “what-if” scenarios, where a set of specific changes are tested (Pesonen et al., 2000). Only a few studies (10%) created predictive (3 studies) or normative scenarios (1 study).

Although the studies are about the future, the large majority (29) considers only currently dominant (incumbent) technologies, while a few studies cover both dominant and emerging technologies (9).

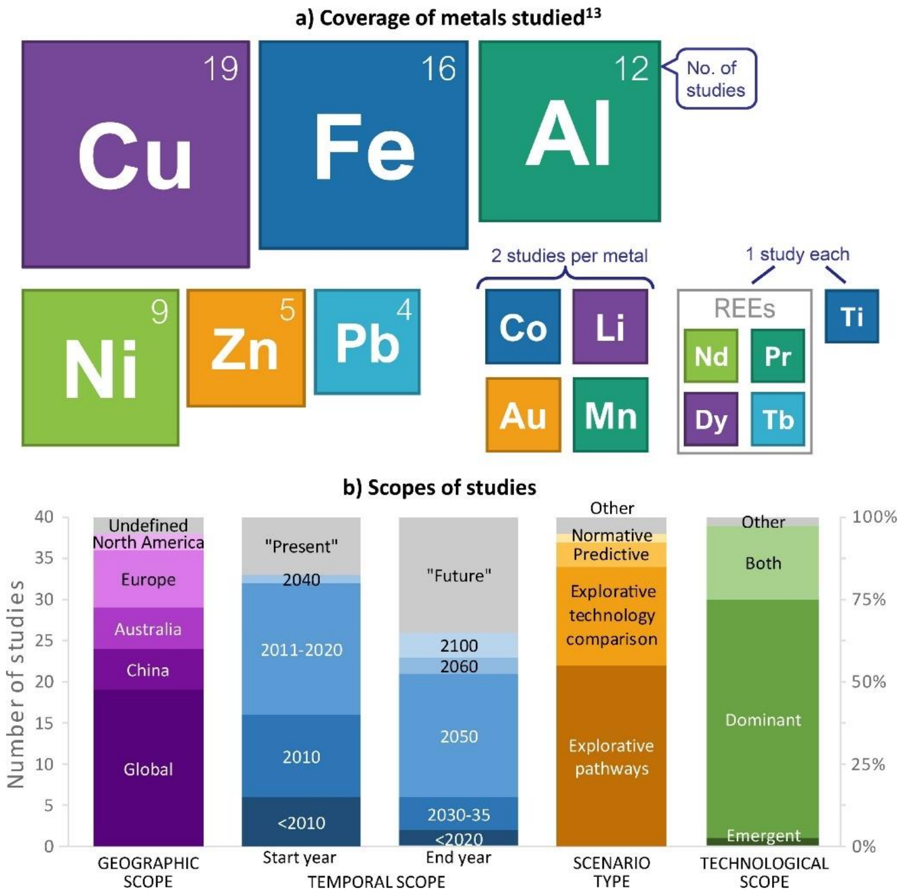


Fig. 2: Overview of metals and scopes covered in the reviewed studies. a) Coverage of metals studied and number of studies per metal[13]; b) Distribution of scope choices and scenario types for reviewed studies. The temporal scope refers to the first and last year analysed. Definitions of terms are provided in Table 1. 'Europe' and 'North America' refer to specific countries on the continent. For underlying data, see Harpprecht et al. (2023), Table A.1. REEs: rare earth elements.

[13] **The 40 publications reviewed by metal: Al**: Farjana, Huda, Mahmud (2019); Li, Zhang, Li, He (2017); Li, Zhang, Niu, Yue (2021); Manjong et al. (2021); Norgate and Haque (2010); Norgate and Jahanshahi (2011); Norgate et al., (2007); Pauliuk et al. (2021); Tan and Khoo (2005); van der Voet et al. (2019); Yokoi, Watari and Motoshita (2021); Zhong et al. (2021); **Au**: Farjana and Li (2021); Kumar Katta, Davis, Kumar (2020); **Cu**: Alexander et al. (2021); Ciacci et al. (2020); Dong et al. (2020); Elshkaki, Graedel, Ciacci, Reck (2016); Harpprecht et al. (2021); Kuipers et al. (2018); Manjong et al. (2021); Memary et al. (2012); Mudd et al. (2013); Norgate and Haque (2010); Norgate and Jahanshahi (2011); Norgate et al., (2007); Northey et al. (2013); Pauliuk et al. (2021); Song et al. (2017); van der Voet et al. (2019); Watari et al. (2022); Yokoi, Watari and Motoshita (2021); Zhong et al. (2021); **Co**: Rinne et al. (2021); van der Meide et al. (2022); **Fe**: Chisalita et al. (2019); Koroma et al. (2020); Kumar Katta, Davis, Kumar (2020); Li, Chu, Tang, Liu, Guo, Yan, Liu (2022); Norgate and Haque (2010); Norgate and Jahanshahi (2011); Norgate et al., (2007); Pauliuk et al. (2021); Ren, Liu, Ren (2021); Ryberg et al. (2018); Sacchi et al. (2022); Suer et al. (2021); van der Voet et al. (2019); Wang et al. (2021); Yokoi, Watari and Motoshita (2021); Zhong et al. (2021); **Li**: Ambrose and Kendall (2020); Manjong et al. (2021); **Mn**: Manjong et al. (2021); van der Voet et al. (2019); **Ni**: Eckelman (2010); Elshkaki, Reck, Graedel (2017); Harpprecht et al. (2021); Khoo, Haque, Woodbridge, McDonald, Bhattacharya (2017); Manjong et al. (2021); Norgate et al., (2007); van der Voet et al. (2019); Yokoi, Watari and Motoshita (2021); Zhong et al. (2021); **Pb**: Harpprecht et al. (2021); van der Voet et al. (2019); Yokoi, Watari and Motoshita (2021); Zhong et al. (2021); **Ti**: Norgate et al., (2007); **Zn**: Harpprecht et al. (2021); Pauliuk et al. (2021); van der Voet et al. (2019); Yokoi, Watari and Motoshita (2021); Zhong et al. (2021); **REEs (i.e., Dy, Nd, Pr, Tb)**: Langkau and Erdmann (2020).

2.3.2. Trends and drivers of future impacts of metal supply

Fig. 3 illustrates the expected trends of future GHG emissions for all metals aggregated (see a)-b)) or in detail by metal for the six metals investigated by most studies (see c)). It compares specific impacts, i.e., per kg metal produced, and demand-related impacts, i.e., of a future annual demand. Demand-related impacts consider the future demand of primary, and optionally of secondary metal production.

In total, specific GHG impacts are assessed more often (63 times) than demand-related impacts (48 times) (Fig. 3.a-b).

At a high-level perspective (Fig. 3.a-b), no clear consensus exists whether specific and demand-related GHG emissions will increase, decrease or stay about constant in the future. The results seem to depend on the respective study, its scenarios, scenario variables and assumptions.

Yet, Fig. 3.a-b) reveals the following differences between demand-related and specific impacts: for demand-related impacts, a small majority of the results (54%) state that GHG emissions may increase, while for specific GHG emissions, a majority of 65% declare that impacts may decrease in the future.

In both cases, however, these majorities are undermined by results claiming the respective opposing impact trend or stating that the trend direction depends on the choice of scenario.

For the detailed results per metal (Fig. 3.c), the same conclusion can be drawn: the results for future GHG impacts per metal are not univocal. A high variety of impact trends are reported in literature even for an individual metal.

The only development where literature seems to fully agree is that for copper, aluminium and lead specific GHG emissions of the respective metal markets may decrease. Here, the main drivers are a greener electricity mix and increased secondary production shares. However, it is very uncertain whether these improvements will be sufficient to compensate for the effect of a rising demand, as there seems to be little confidence that demand-related GHG impacts may also decrease (see high shares of “increase” or “direction depends on scenario” for demand-related impacts).

When comparing impact trends of primary production and of the market mix, i.e., primary + secondary production (see Fig. 3.c), we see that results differ as well. This highlights the need to consider future secondary supply shares which may considerably lower environmental impacts. However, primary supply impacts are to date more often examined than impacts of market mixes (primary + secondary supply).

It stands out that demand-related impacts of all metal markets are considered unlikely to decrease (see Fig. S2). For both GHG emissions (11 studies) and other impact categories (only 7 studies), not a single study states a solely decreasing trend for demand-related impacts of markets. The trends are either expected to increase (70% of results) or depend on the scenario (30%). For impacts other than GHGs, there is strong evidence for an increasing trend, which represents 92% of the results with only 8% representing a dependency on the scenario choice. Interestingly, demand-related impacts of metal markets are so far rarely assessed (14 of 39 studies, i.e., 36%) despite their high coverage and relevance for global sustainability goals.

Generally, most studies assess GHG emissions (87% of studies), other impact categories are less often assessed, i.e., by 49% of studies (see Fig. S2).

More details about the trends and drivers of future impacts per metal are provided in the next sections. The results of the remaining metals are presented in the SI, section S2.

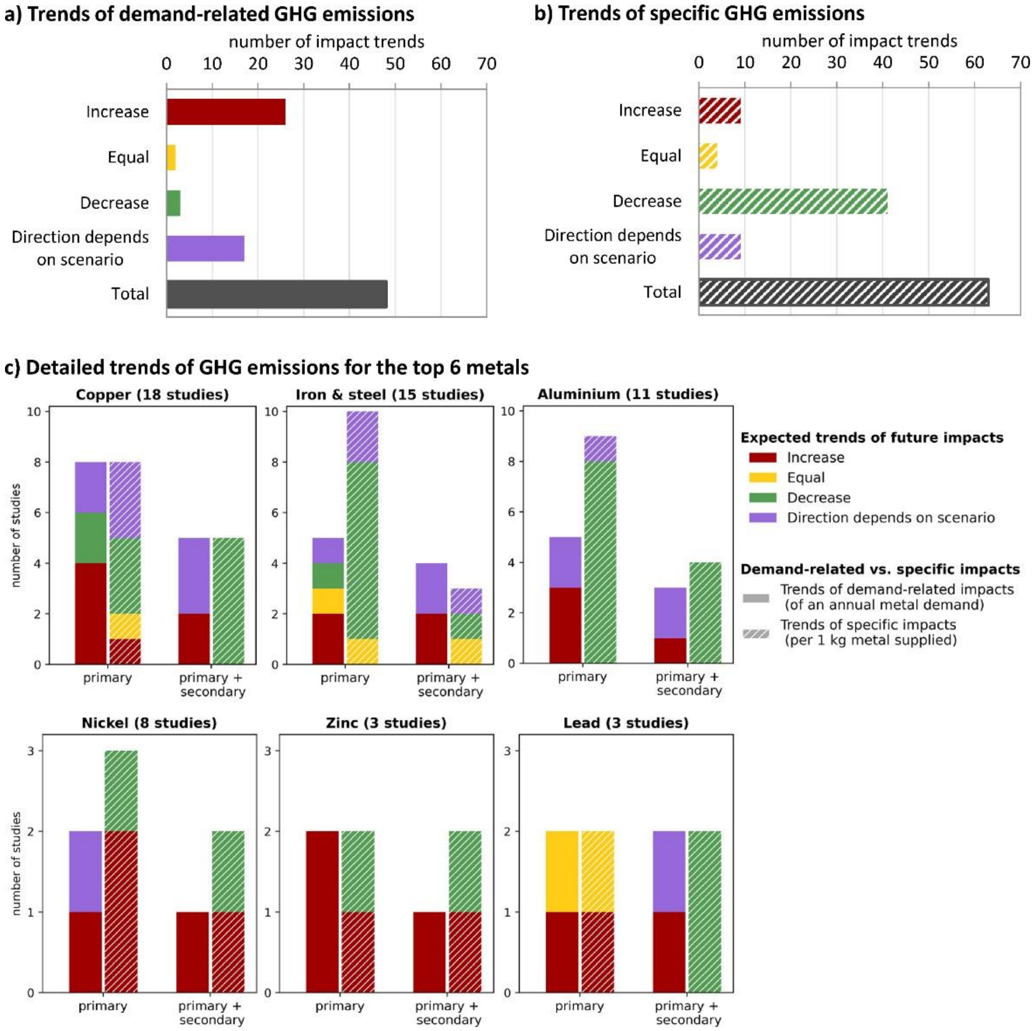


Fig. 3: Trends of future GHG emissions according to the reviewed studies. a) and b) aggregate the data for all metals. C) Results only for the six metals studied the most (n>=3). Demand-related impacts (solid bar) represent trends of GHGs of a future annual demand of a metal. Specific impacts (hatched bars) show trends per 1 kg metal produced. Results for impacts other than GHGs and the other metals are provided in the SI (see Fig. S2.b). Note: Some studies, e.g., Li et al., (2017), investigate CO_2 emissions instead of CO_2-eq.. They are aggregated here since the trend of CO_2 emissions and of CO_2-eq. are likely to coincide. Papers which do not quantitatively determine any impacts are excluded in this analysis, i.e., Pauliuk et al. (2021) and partly Norgate and Jahanshahi (2011). Thus, the number of studies may deviate from Fig. 2.a). For underlying data, see Harpprecht et al. (2023), Tables B.4-5, C.1.

Copper

Copper has been investigated by 18 of the scenario studies. From these studies, a consensus emerges that a decline of mined ore grades may increase specific emissions of primary production. Historic trends clearly show that the concentration of copper in mined ores is declining (Memary et al., 2012; Northey et al., 2013), which increases water and energy requirements as well as toxicity impacts (Dong et al., 2020; van der Voet et al., 2019).

For specific GHG emissions, a decline is often anticipated, especially for the market mix. Thus, the effect of lower ore grades can potentially be offset by increased recycling shares and more renewable electricity (van der Voet et al., 2019; Watari et al., 2022; Yokoi et al., 2022).

Some studies also report impacts beyond climate change. The trend of these impacts is partly identified as independent of that of GHG emissions, e.g., for human toxicity or metal depletion (Harpprecht et al., 2021). These impacts originate from direct mining emissions and are therefore not influenced by common measures against GHG emissions, such as a greener electricity mix (Harpprecht et al., 2021).

Copper demand grows in all scenarios, driving up the demand-related impacts. This trend cannot be offset by increased recycling shares (van der Voet et al., 2019; Watari et al., 2022). Recycling shares are likely to rise as demand levels off and recovery rates increase. The benefits of higher recycling shares are much larger than of pure energy efficiency measures (Yokoi et al., 2022).

Iron and steel

Future impacts of iron and steel are investigated by 15 studies. Multiple studies stress that GHG intensities of primary steel production cannot substantially decrease with current production technologies as these require fossil fuels and do not offer further potential for efficiency improvements (van der Voet et al., 2019; Wang et al., 2021). Wang et al. (2021) demonstrate that specific GHG emissions may not be considerably reduced through efficiency improvements of the current primary and secondary production technologies which have been stagnating in the last years. A switch to low-carbon technologies is required to decrease GHG intensity of primary production (van der Voet et al., 2019; Wang et al., 2021). Some studies show that novel production technologies can considerably reduce specific climate change impacts of primary steel supply, such as carbon capture and storage (Chisalita et al., 2019) and hydrogen-based direct reduction (Koroma et al., 2020). Sacchi et al. (2022) reveal that specific climate change impacts of the steel market can be reduced by 45% if secondary production shares are increased and electricity supply is decarbonized.

However, it is expected that global steel demand may be growing in the next decades (Ryberg et al., 2018; Wang et al., 2021; Yokoi et al., 2022), by a factor of up to 3.5 (van der Voet et al., 2019) which increases primary steel production and thus also demand-related global GHG emissions from steel (Kumar Katta et al., 2020; van der Voet et al., 2019; Wang et al., 2021). This rise in emissions can only be avoided through drastic measures, which limit steel demand, (e.g., through material efficiency improvements, increase recycling shares) or rigorously reduce GHG intensity of primary production (van der Voet et al., 2019; Wang et al., 2021; Yokoi et al., 2022).

Only a few studies assess impact categories other than climate change for future steel production. Van der Voet et al. (2019) found that other impacts follow similar trends as climate change impacts. Likewise, Norgate et al. (2007) found that switching to bath smelting processes for stainless steel reduces both climate change and acidification impacts. On the other hand, Chisalita et al. (2019) stress that the application of CCS for blast and basic-oxygen furnaces may reduce specific climate change impacts but is likely to increase impacts in almost all other impact categories independent of the type of CCS technology applied.

Aluminium

Future impacts of aluminium production have been discussed by 11 publications. Specific GHG emissions of aluminium production are expected to decline in most scenarios. For other impact categories, however, no consensus seems to exist.

The main driver to lower specific GHG emissions is switching to a more renewable electricity mix (Farjana et al., 2019a; van der Voet et al., 2019). However, this may increase other impacts, such as human toxicity (Farjana et al., 2019a) and metal depletion (van der Voet et al., 2019). Other emission reduction options are more energy-efficient technologies (Li et al., 2017; Manjong et al., 2021; Norgate and Jahanshahi, 2011), especially in the metal extraction and refining stages (Norgate and Jahanshahi, 2011), waste reduction during production (Tan and Khoo, 2005), and increased recycling rates (van der Voet et al., 2019). There is no evidence of declining aluminium ore grades (Norgate and Jahanshahi, 2011; van der Voet et al., 2019).

GHG emissions of aluminium production are expected to increase due to growing demand in the next decade (Li et al., 2017; van der Voet et al., 2019). Later, high recycling rates may lower demand-related GHG emissions again (van der Voet et al., 2019).

Nickel

Future impacts of nickel production are uncertain, though there is a strong indication that both specific and demand-related climate impacts may increase. Anticipated increases of demand-related impacts are driven by rising demand and ore grade decline (Elshkaki et al., 2017; SSP 2-5 in Yokoi et al., 2022; van der Voet et al., 2019). Likewise, the expected trend of specific impacts may increase due to declining ore grades (Markets First scenario in van der Voet et al., 2019 and SSP 2-5 in Yokoi et al., 2022; Harpprecht et al. 2021), unless electricity supply is deeply decarbonized (Harpprecht et al., 2021; van der Voet et al., 2019) and recycling shares are increased (Harpprecht et al., 2021). Next to these future scenarios, other analyses investigated production variables independent of their temporal evolution. They confirm the results that ore grade is a major driver for energy use and consequently for climate change impacts (Manjong et al., 2021; Eckelman, 2010) and that a greener electricity mix could substantially reduce climate impacts (Khoo et al., 2017; Eckelman, 2010). There are thus strong indications that climate change impacts of nickel production may increase in the future due to declining ore grades driven by growing demand, though a greener background electricity mix and higher recycling shares may partially compensate these increases in impacts.

Zinc

Specific climate change impacts of zinc production are not expected to change substantially. They either have a slight decline (Harpprecht et al., 2021; van der Voet et al., 2019; Yokoi et al., 2022) or slight increase (van der Voet et al., 2019) up to 2050, depending on the background electricity supply. The effect of declining ore grades is minor compared to other metals. It is likely to be offset by a greener electricity mix in most impact categories, except for human toxicity and metal depletion (Harpprecht et al., 2021). Specific climate change impacts are likely to be influenced most by greening the background electricity mix. When considering demand-related impacts, the picture is clearer: both van der Voet et al. (2019) and Yokoi et al. (2022) find increasing impacts in all scenarios, despite improvements in the background like a more renewable electricity mix.

Lead

The specific climate change impact of primary and secondary lead production is expected to decrease driven by the energy transition (Harpprecht et al., 2021; van der Voet et al., 2019; Yokoi et al., 2022). According to Harpprecht et al. (2021), the effect of declining lead ore grades can be overcompensated by increasing recycling shares for specific market impacts.

On the other hand, demand-related environmental impacts may still increase driven by demand and despite phasing-out strategies and increasing recycling rates (van der Voet et al., 2019). Likewise, Yokoi et al. (2022) indicate that the energy transition, recycling shares and decreasing metal intensity are unable to fully compensate growing demand which results in increasing GHG emissions for SSP1-4. Ore grade decline and an energy transition play a smaller role for lead than for other metals analysed by van der Voet et al. (2019).

Others

In the following, we discuss metals investigated by one or two articles (see Fig. S2.b). Manganese, cobalt and lithium are highly relevant as they are enablers of electrification technologies, such as batteries (Manjong et al., 2021; Rinne et al., 2021). Increasing demand scenarios result in higher demand-related impacts for these three metals (Ambrose and Kendall, 2020; van der Meide et al., 2022; van der Voet et al., 2019), but the effect may be partially mitigated with a greener electricity mix (Manjong et al., 2021; van der Meide et al., 2022; van der Voet et al., 2019). Furthermore, declining ore grades may increase specific impacts (Manjong et al., 2021; van der Meide et al., 2022), although van der Voet et al. (2019) found no evidence of a current grade decline of manganese ore. For lithium, the use of low-grade ores is expected to grow significantly, but adapting the production routes to the ore grade may partially mitigate the impacts (Ambrose and Kendall, 2020).

Similarly, the rare earth elements neodymium, dysprosium, praseodymium, and terbium are crucial for magnets, e.g., in electric cars (Langkau and Erdmann, 2021). Langkau and Erdmann (2021) state that specific environmental impacts may most effectively be reduced through mitigation measures preventing illegal mining and improving environmental standards in China. Despite such improvements, the study reports an increase of global demand-related impacts for scenarios with medium and high future demand. Reductions in climate change impacts are only achieved in scenarios with major climate action and low future demand.

Two studies investigated gold as a precious metal without a direct role in the energy transition. Farjana and Li (2021) assessed twelve impact categories for four scenarios on Swedish primary and secondary production. They indicate that an increase in gold recycling would decrease the specific emissions of the gold market. Kumar Katta et al. (2020) assessed the environmental benefit and cost of 24 GHG mitigation options for the Canadian primary production of gold and developed seventeen pathways from 2018 to 2050. In most of the pathways, growing demand increases GHG emissions. However, emissions could decrease by 20% if diesel haul trucks for ore extraction are replaced with electric and hybrid vehicles and by reducing the underground mining ventilation requirements.

2.3.3. Scenario variables

We identified 15 scenario variables common within the reviewed literature, which we grouped into five categories: background system, mining, processing & refining, metal markets, and energy use. Table 2 provides the detailed description of each variable.

Fig. 4.a illustrates the number of occurrences of each variable. Each study uses 2 to 9 scenario variables to model the development of metal production. The most studied scenario variables are background electricity mix and ore grade. These are included in 26 and 21 out of 40 reviewed studies respectively. They are followed by the variables of general energy efficiency improvements, metal demand and recycling shares (all 19 studies). Furthermore, the deposit type (12 studies), mining efficiency, production locations and market shares of refining methods (all 10 studies) are frequently investigated.

For the background system, studies mostly modelled changes in the electricity mix. Only 5 of 40 studies integrated background variables other than the electricity mix (Harpprecht et al., 2021; Koroma et al., 2020; Langkau and Erdmann, 2021; Sacchi et al., 2022; Zhong et al., 2021). Since this approach is not widely used, either due to technical challenges or lower relevance, there is a general lack of background scenarios for many variables.

In the mining stage, the scenario variable most used is ore grade. Ore grade is important for certain major metals (Cu, Ni, Zn, Pb), because their mined ore grade has been decreasing over time which can negatively affect the environmental performance of primary production (Harpprecht et al., 2021; van der Voet et al., 2019). Two variables are closely linked to ore grade, namely production location and deposit type.

Future developments in the stage of processing and refining are studied the least. The reason could be that the technologies for smelting and refining are well-established and have been optimized for several decades, thus offering fewer options for technology improvement. This applies for example to copper, but depends on the metal. For instance, iron and steel, form an exception, as the smelting process via the blast furnace has a high emission-intensity and needs to be replaced by alternative or emerging technologies in the future. Such technological innovation is accounted for by the variables of technology-switch or the application of CCS. Efforts to retrieve refining information can be valuable as it provides insight in technology development and the implications of new mines (Ambrose and Kendall, 2020; Mudd et al., 2012).

Table 2: Description of scenario variables used to model future impacts of metal production for each variable category.

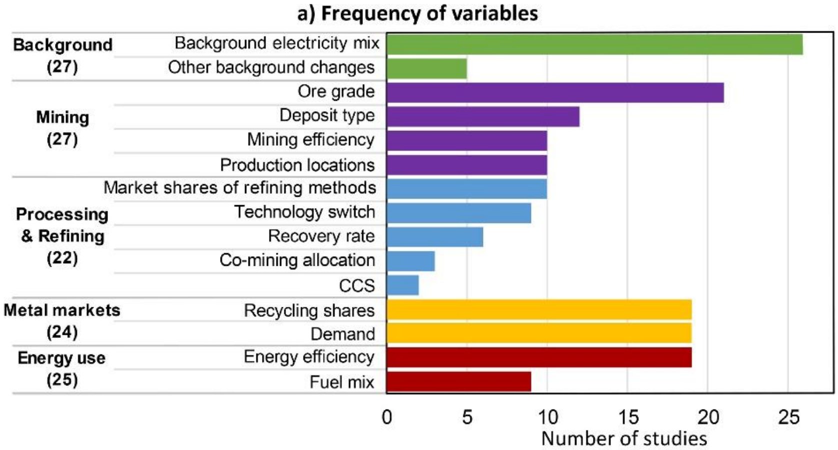
Variable category	Scenario variables	Description
Background system	Background electricity mix	Scenarios for electricity supply in the background system of the LCA model
	Other background changes	Changes in upstream production, e.g., of chemicals
Mining	Ore grade	Metal concentration in the mined ore
	Deposit type	Mineralogical type of the ore
	Production locations	Changes in market shares between different production locations
	Mining efficiency	Efficiency improvements specifically during mining, e.g., energy efficiency, technological improvements
Processing & refining	Market shares of refining methods	Market share of refining technologies for primary production (e.g., hydro- vs. pyrometallurgical refining)
	Co-mining allocation	Allocation factor for allocating impacts between co-mined ores, e.g., changes in metal composition of ore or changing prices of co-mined metals
	Recovery rate	Material efficiency of beneficiation and refining
	Technology switch	A novel or emerging technology is used instead of the currently dominant technology in the foreground
	Application of CCS	Carbon capture and storage is applied to processing and refining technologies
Metal markets	Recycling shares	The ratio between primary and secondary production
	Demand	Production volume of a metal in a region to quantify demand-related impacts
Energy use	Energy efficiency	Energy savings or other improvements in any process within the metal supply chain, e.g., in mining, or processing and refining
	Fuel mix	Different fuels are used on-site for the technology in the foreground, e.g., hydrogen or electrifying heat supply

It is remarkable that co-mining is addressed in only three studies (7.5%), even though the choice of allocation method can have a profound influence on the results (Langkau and Erdmann, 2021; van der Meide et al., 2022). Especially less-abundant metals are mainly produced as by- or co-products (Nassar et al., 2015), making allocation a key variable.

The variables of demand and recycling share are mostly assessed in combination, since the recycling share is constrained by the ratio of end-of-life material versus demand.

Within the category of energy use, the fuel mix (e.g., increasing the share of biomass (Koroma et al., 2020), hydrogen (Suer et al., 2020) or electrifying heat supply (Watari et al., 2022)) is less often modelled than general energy efficiency improvements.

Ultimately, it is surprising that background changes, especially for the electricity mix, are considered by so many publications. We noticed that the technical approaches to incorporate them as background scenarios differ. Some studies apply automated approaches, e.g., from Mendoza Beltran et al. (2018), Steubing and de Koning (2021) or Sacchi et al. (2022), which are transparent and reproducible. They allow to systematically relink new process within the entire database. In contrast, manual approaches relink new processes usually only to a selection of processes, thus not realizing a complete incorporation into the entire database (e.g., Koroma et al., 2020; van der Voet et al., 2019; Watari et al., 2022). Although all approaches adapt processes in the background system, consistency and depth differ.



b) Scenario variables studied per metal

Scenario variables		Cu	Fe	Al	Ni	Zn	Pb	Mn	Au	Co	Li	REEs	Ti
Back-ground	BG electricity mix	12	8	10	7	5	4	2	1	2	2	0	0
	Other BG changes	2	3	1	2	2	2	0	0	0	0	1	0
Mining	Ore grade	16	0	1	9	4	4	1	0	1	2	0	0
	Deposit type	4	1	0	2	0	0	0	1	1	2	1	0
	Production locations	4	3	1	1	0	0	0	0	0	2	1	0
	Mining efficiency	3	4	1	0	0	0	1	1	2	0	1	0
Process-ing & Refining	Shares of refining method	6	0	0	2	0	0	0	0	1	1	1	0
	Technology-switch	4	5	1	0	0	0	0	0	0	0	0	1
	Recovery rate	1	0	1	1	0	0	1	1	0	0	1	0
	Co-mining allocation	1	0	0	0	0	0	0	0	1	0	1	0
	Application of CCS	0	2	0	0	0	0	0	0	0	0	0	0
Metal markets	Recycling shares	10	7	6	5	3	3	1	1	1	0	0	0
	Demand	11	8	7	2	3	2	1	1	1	1	1	0
Energy use	Energy efficiency	9	8	9	2	1	0	0	0	0	0	1	0
	Fuel mix	4	4	2	3	1	1	0	1	0	1	0	0
Average variables per metal		**4.6**	**3.3**	**3.3**	**4.0**	**3.8**	**4.0**	**3.5**	**3.5**	**5.0**	**5.5**	**9.0**	**1.0**
Total number of studies		**19**	**16**	**12**	**9**	**5**	**4**	**2**	**2**	**2**	**2**	**1**	**1**

Fig. 4: Overview of studied scenario variables in the 40 studies. a) Frequencies of variables grouped by overarching categories or life-cycle stages. Numbers in brackets refer to the total number of studies per variable category. b) Scenario variables by metal. For the respective publications per metal, see Fig. 2.a). For underlying data see Harpprecht et al. (2023), Tables A.1, C.2. BG: background; REEs: rare earth elements.

Fig. 4.b provides an overview of the identified scenario variables per metal illustrating existing scenarios as well as potential research gaps. Studies implemented 1.0 (titanium) to 9.0 (REEs) variables per metal. While the proportion of studies that address demand is fair (≥50%) for most metals, nickel demand has been studied in only 2 of 9 studies. For the metals of copper, gold, lithium, scenarios considering other BG changes, production locations, technology-switch, application of CCS, and energy efficiency are mostly lacking. The application of CCS is so far only considered for iron and steel. For zinc and lead, existing studies cover mostly the same variables but lack scenarios for the mining and refining stages. For the REEs (neodymium, dysprosium, praseodymium, terbium), only 1 study was identified, however that one realized the maximum of 9 variables.

2.3.4. Scenario modelling approaches and data sources

Our review indicates a high variety of scenario modelling approaches and data sources. We identified 229 unique data sources which were used for generating scenarios by the 40 publications (see Table S3). A complete overview of the scenario modelling approaches and data sources of each study is provided in a repository (Harpprecht et al., 2023). Many variables have no common modelling approach across studies. Additionally, modelling approaches are often not reported consistently, making it challenging to identify patterns.

Fig. 5 illustrates the identified categories for scenario modelling approaches and data sources for variables which appear in more than 10 publications.

For the modelling approaches, certain approaches are common across variables and used several times within a variable (see Fig. 5.a). What-if scenarios and extrapolation of historic trends are used the most (in 5 out of 6 variables investigated), followed by scenarios from IAMs or energy models (used 4 times), with the most applied models being IEA, IMAGE or Remind and shared socio-economic pathways (SSP) scenarios. Less frequent approaches are using scenario data or assumptions from literature (3 times) or from MFAs (2 times). Scenarios of other models are additionally used, e.g., the GeRS-DeMo (Northey et al., 2014) for ore grade data or logistic growth models for demand scenarios (Ambrose and Kendall, 2020).

For some variables, our analysis reveals that certain approaches are prevailing, i.e., an approach is used by more than 40% (see Fig. 5.c). This is the case for the variables of i) background electricity mix, with scenarios from IAMs or energy system models representing 54%; ii) demand, with the MFA approach reaching 56%; and iii) ore grade, where exploration of historic trends accounts for 48% of the modelling approaches. For recycling shares, MFA and what-if scenarios are with 32% each quite common. In contrast, the variables of deposit type and energy efficiency exhibit a high diversity of modelling approaches.

a) Most common modelling approaches

Modelling approaches	BG electricity mix	Ore grade	Recycling share	Demand	Energy efficiency	Deposit type
what-if scenarios	x	x	x	x	x	
extrapolation of historic trends		x	x	x	x	x
scenarios from IAMs or energy models*	x		x	x	x	
from literature		x	x		x	
MFA			x	x		

b) Most common data sources

Data sources	BG electricity mix	Ore grade	Recycling share	Demand	Energy efficiency	Deposit type
*Scientific literature***		x	x	x	x	x
IAMs or energy models	x		x	x		
Derived within the publication	x		x	x		
Governmental data	x	x	x			
Metal-specific organization		x			x	

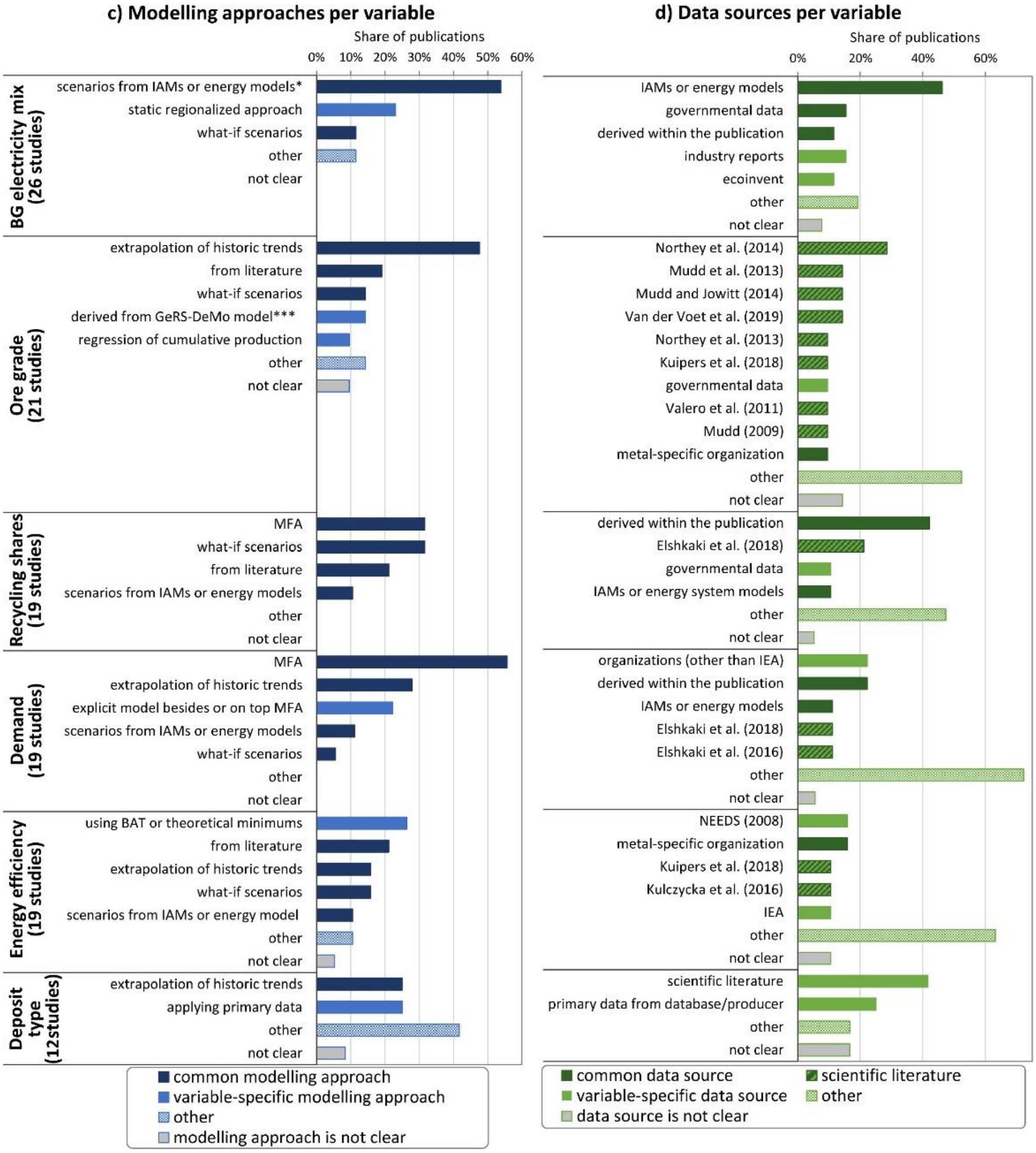


*Fig. 5: Identified categories for scenario modelling approaches and data sources for variables which appear in more than 10 studies. The categories are not mutually exclusive. "not clear" indicates that the required information cannot be derived from the original publication. If no bar is shown, the value is 0%. For underlying data see Harpprecht et al. (2023), Tables A.1-2, C.3. *The 54% can be disaggregated into the following models (not mutually exclusive): IEA: 23%; IMAGE: 15%; REMIND: 4%; LEAP: 4%; MESSAGEix: 4%; SSPs not specifying IAM: 8%. **Scientific literature includes also individual scientific publications. ***GeRS-DeMo: Geologic Supply–Demand Model.*

For data sources, we found fewer similarities across variables (see Fig. 5.b). The most common is scientific literature, which IAMs belong to (e.g., Riahi et al.; 2017; Baumstark et al. 2021; Stehfest et al., 2014; Mendoza Beltran et al. 2020). Data sources are mostly variable-specific (see Fig. 5.d) and very diverse even within a variable (see high contribution of other). However, scenario data from IAMs and energy models is used frequently in the variables of background electricity mix (46%), recycling shares (11%), energy efficiency (11%) and demand (11%). In contrast, the variables of ore grade and deposit type require data of higher resolution, which is usually out of the scope of IAMs and energy models. Thus, studies use metal-specific data sources for ore grade and deposit types. Primary data is a major data source only for deposit type (25%). For recycling shares, most of the studies (42%) derive scenarios within the publication, e.g., via MFA, or use scenarios from Elshkaki et al. (2018) (21%). Despite the high variety of data sources, several peer-reviewed articles appear as dominant sources for scenario data for ore grade (Kuipers et al., 2018; Mudd, 2009; Mudd et al., 2013; Mudd and Jowitt, 2014; Northey et al., 2014, 2013; Valero et al., 2011; Van der Voet et al., 2019), recycling shares (Elshkaki et al., 2018), demand (Elshkaki et al., 2018, 2016), or energy efficiency (Kuipers et al., 2018; Kulczycka et al., 2016).

2.3.5. Adherence to FAIR data principles

The analysis of data disclosure of the reviewed studies revealed that 25% of studies did not publish LCI or scenario data at all. The rest of the studies published data but the completeness of the data is very difficult to determine as an external reviewer. Many different data formats were used (tables in the main publication, in the supplementary PDF, in spreadsheets, etc.). No common format could be identified. Moreover, no common approach for documenting scenario data, assumptions and meta-data could be identified.

The keyword search for FAIR data principles (Wilkinson et al., 2016) did not yield many results in the reviewed studies. This reveals that these principles are not commonly used yet. Only the following keywords could be found: “python” (10% of studies), “superstructure” (10%), “repository” (7.5%), “zenodo” (5%), “github” (2.5%). For a full list of the other keywords, see Harpprecht et al. (2023), Table B.3.

50% of the studies used ecoinvent as database for the background system but the versions of ecoinvent vary (version 2.1, 2.2, 3.1-3.8). The rest of the studies reported to use other databases (e.g., GaBi) or data from unspecified sources (30%).

The term of background scenario or background system are divergently used by practitioners. Furthermore, using different background databases makes results not only less comparable but also makes it difficult to reuse the scenario data for new studies which apply a newer version of the background database (Miranda Xicotencatl et al., 2023). Only three studies (Harpprecht et al., 2021; Sacchi et al., 2022; van der Meide et al., 2022) released scenario data versions compatible with newer ecoinvent versions, e.g., by updating their scenario data after the initial publication.

2.4. Discussion

2.4.1. Key findings

This study aimed to provide a systematic overview of existing research about future environmental impacts of metals. We identified 40 publications (section 2.3.1) and reviewed their results (section 2.3.2), i.e., reported impact trends, and methods regarding studied scenario variables (section 2.3.3), scenario modelling approaches and scenario data sources (section 2.3.4).

Our results show that the reviewed studies address only 15 metals (see Fig. 2). The majority of publications focuses on assessing future impacts of the supply of major metals, like copper, iron and steel, or aluminium. While various studies investigate future demand of minor metals, such as lithium, cobalt, or rare earth elements, their future impacts are rarely studied. Impact assessments of certain metals are completely lacking despite their significant global production impacts, e.g., calcium, magnesium, or silver (Nuss and Eckelman, 2014).

Most studies investigated specific primary supply impacts and GHG emissions. There is a lack of studies addressing potentially other relevant impacts, such as land use, water use, or related biodiversity loss, as well as demand-related impacts of future global metal demand (Fig. 3).

Among the reviewed studies, no clear consensus seems to exist regarding the future trends of impacts across all metals. Also studies on single metals regularly find diverging impact trends, making it difficult to draw conclusions. The results seem to depend on the scenario narratives, scenario variables and assumptions. Nevertheless, we can identify the following general trends (Fig. 3):

- Specific impacts (i.e., impacts per kg metal produced) are likely to decrease.
- Demand-related impacts (i.e., impacts for the total amount of metal supplied) are expected to increase.
- Overall, we hence see that relative decoupling may occur: impacts per kg metal may decrease, e.g., due to the diffusion of low-carbon technologies, but rise in demand will probably outstrip these gains.
- For copper, aluminium and lead, there is a consensus in literature that specific GHG emissions of the respective metal markets will decrease driven by a greener electricity supply and increased recycling shares. Yet, this may be insufficient to compensate for a rising demand and to lower demand-related climate change impacts.

Within the 40 publications, we identified 15 scenario variables (see Fig. 4). The most common variables are: background electricity mix, ore grade, recycling shares, demand, and energy efficiency improvements. There is not a universal variable that governs the impact trends of all metals. Each trend is a result of multiple variables, which can have reinforcing or counteracting effects on impacts. Yet, an increasing demand and demand-related impacts seem to be likely for all metals.

Our overview of scenario modelling approaches reveals a high variety of modelling approaches for each variable. The most common approaches are what-if scenarios, extrapolation of historic trends and using scenarios from IAMs or energy models (Fig. 5.a, c). Likewise, data sources are highly diverse. We identified 229 unique data sources for the reviewed scenario variables (see Fig. 5.b, d; provided in Table S3 and Table A.2 in Harpprecht et al. (2023)).

Publishing complete datasets in compliance with FAIR data principles is uncommon (section 2.3.5). A common data format and streamlined documentation is needed to enable a combination of scenario variables from different studies.

2.4.2. Identified challenges and recommendations

Based on the literature review, we identified challenges and provide recommendations to overcome these in Table 3. Recommendations are grouped into three areas: 1. Insights in future impacts of metals; 2. scenario methods; and 3. data.

Some challenges that we identified for metal production scenarios also apply to prospective LCA studies in the broader sense. A prominent example is the challenge to combine scenarios, for which a common LCI and scenario data format needs to be developed.

Table 3: Challenges of and recommendations for the assessment of future impacts of metals and the use of scenarios.

Challenge	Recommendation
1. Insights in the future impacts of metals	
Currently, only 15 metals are investigated. The current body of literature does not address future impacts of many important metals. For example, some metals used in clean energy technology (Liang et al., 2022) have not been studied (see Fig. 2.a).	**More prospective LCAs are required** for metals essential for energy technologies to better understand the impacts of future energy systems, as well as for metals causing high impacts at a global scale (see, e.g., Nuss and Eckelman (2014)).
Studies on demand-related impacts of metals mostly found increasing future impacts due to the rising demand, which cannot be compensated by decreasing specific impacts (see Fig. 3). Yet, the majority of studies disregard future demand and investigate specific impacts only.	While it is helpful to identify solutions to decrease specific impacts, it is required to **also consider demand developments** to determine impact trends of a total demand. For this, it is required to couple supply and demand scenarios which ideally are developed based on consistent assumptions and storylines, as it has also been recommended by Watari et al. (2020).
The influence of future demand developments on the supply strategies (e.g., novel production technologies) **are not considered by many studies** (Fig. 4.b)), although demand growth can be a main driver of rising impacts (Fig. 3).	**More research is needed for the metals where demand is expected to grow strongly.** This can guide the development of required new production capacities towards more sustainable practices. Ideally, studies are conducted in collaboration with industry associations and technology experts.
Our review revealed 15 variables as being used in literature to date for 15 metals. Future electricity mix, recycling shares, and demand are identified as key drivers. Yet, the modelled **variables are mostly specific to certain metals** and each study uses a different set of variables and data sources (see Fig. 4).	**Future studies could learn from our overview of commonly used variables, modelling approaches and data sources** (see Fig. 4, 5 and Harpprecht et al. (2023), Tables A.1-2). Moreover, already published background scenarios and LCA models could be used as a basis for new prospective LCI datasets. While our work can provide guidance, metal-specific expert knowledge is still required for scenarios of other metals.
Studies report diverging findings due to different sets of variables, modelling approaches and assumptions (Fig. 3). Thus, future impacts of a metal are difficult to determine.	**Future research should aim at identifying the key variables for each metal and provide them in a harmonized and reusable way.** Thereby, the influence of existing variables as well as of new variables could be evaluated quantitatively.
Assessing impacts beyond GHG emissions is uncommon (see SI Section S2), as it has also been found by Watari et al. (2021), even though it is well known that metal production causes other severe impacts, such as toxicity (Nuss and Eckelman, 2014; Reinhard et al., 2019) and might increase biodiversity loss (Sonter et al., 2020).	Future studies should not only focus on CO_2 or GHG emissions but **also consider other impact categories to avoid a carbon-tunnel-vision.**

2. Scenario methods	
There is a high variety of different storylines (see section 2.3.4) among and within studies. The majority of explorative pathway scenarios are not based on general storylines, such as the SSPs. This makes comparisons and combinations of scenarios from different studies difficult because of potentially conflicting assumptions (Steubing et al., 2023).	**Using common and well-documented storylines** like the SSPs (Riahi et al. 2017) for the development of scenarios supports comparability, transparency, transferability and reusability of scenarios from different sources. Practical examples are the studies by van der Meide et al. (2022) or Sacchi et al. (2022).
There is a lack of detailed scenarios for many metals from one comprehensive source, such as IAMs. LCA practitioners thus often need to develop their own scenarios. This leads to a high variety of modelling approaches and data sources for each variable (see Fig. 5), and lowers the reusability of these scenarios.	**New, reusable LCA scenarios for metal production could be used to better represent the metal production sectors in integrated models** (e.g., IAMs).
The term of background scenario or background system are divergently used by practitioners. Many different approaches exist to integrate background scenarios, e.g., manual versus automated adaptations (Sacchi et al., 2022).	**A common definition of background scenarios is required** to better distinguish and understand the approaches of different studies.
3. Data	
Input and output data, e.g., specific LCA results or effect of individual scenario variables on impact results, **are often not or insufficiently reported** (see share of “not clear” in SI Fig. S2), which inhibits their interpretation or reuse.	**If possible, all data and metadata should be made available, ideally adhering to the FAIR data principles.** The goal should be to combine scenarios from different sources to determine the overall impact trends, i.e., the joint effect of variables, and effect of individual scenario variables. As illustrated by Mendoza Beltran et al. (2018) and Harpprecht et al. (2021), the effect of different variables cannot be added due to the interlinked nature of LCA models. Thus, variables from different sources need to be combinable in one model to quantitatively assess their individual as well as joint effect and to gain more insights. A workflow for applying FAIR data principles to LCA models is proposed by Ghose (2024).

It is uncommon to publish model input data, such as metal scenario data, unit process data or LCIs, **and no standardized data format exists** (see section 2.3.5). Therefore, most metal scenarios cannot be easily reproduced or reused.	**Some data formats have proven very suitable for LCA models and scenarios,** although no widely acknowledged data format exists. These are the community scenarios by premise (Sacchi et al., 2022) and the superstructure approach of the Activity Browser (Steubing and de Koning, 2021). These formats have successfully been applied to share energy and transport scenarios, and can be used for any scenario.
The documentation of scenarios is not standardized (e.g., storylines, technology-specific assumptions, modelling choices, or choice of background database), as there are no formal guidelines to develop LCA-compatible scenarios for metal production (Bisinella et al., 2021). This reduces transparency, reproducibility and comparability of studies (see section 2.3.5), as it has also been highlighted by Steubing et al. (2023).	**Future research could develop guidelines on how to streamline the documentation of scenario assumptions and modelling approaches.** This could, for instance, include metadata about: · adopted storyline or SSP; · a description of scenario variables, assumptions and their data sources; · source and modifications of reused LCIs; · model and version of (prospective) LCI database (e.g., ecoinvent cut-off v3.9.1). **Guidelines would enhance collaboration and bring several benefits:** increase research reproducibility, facilitate the verification of results, the performance of meta-analysis, and the uptake of findings across disciplines (Bisinella et al., 2021; Hertwich et al., 2018; Wilkinson et al., 2016).
Studies use different background databases (e.g., ecoinvent vs. GaBi) or different versions of databases. For example, this review found studies with 10 different ecoinvent versions (see section 2.3.5). This makes it **difficult to transfer and reuse LCI and scenario data to other studies.**	**LCA practitioners should try to use a scenario data format which simplifies the update to newer database versions** (e.g., Sacchi et al., 2022). Alternatively, updated scenario data for newer versions can be published regularly (e.g., van der Meide et al., 2022). Data repositories, like Zenodo, facilitate such updates. Scenario data can be provided for different database versions or LCA software (Miranda Xicotencatl et al., 2023).

2.4.3. Comparison with previous reviews

Our results largely align with findings of previous literature reviews.

In accordance with our study, Watari et al. (2020; 2021) identified an increase of future metal demand for metals, except for lead, whose demand they found to decrease after its growth until 2050 (Watari et al. 2021). Watari et al. (2020) highlighted a lack of demand scenarios specifically for critical metals and confirm the need to investigate potential environmental consequences of strong demand growth.

Similarly, a lack of studies assessing impacts beyond GHG emissions was also observed by Watari et al. (2021), Schenker et al. (2022), Farjana et al. (2019b) and Picatoste et al. (2022). Watari et al. (2021) and Schenker et al. (2022) additionally stressed the need to consider emission constraints other than GHG emissions, e.g. using the framework of planetary boundaries, and to implement respective policy targets for metal life cycles.

Our result that future recycling shares is among the most common variables accords with Watari et al. (2021), who thus recommended a wider perspective including the entire life cycle. Similarly, Schenker et al. (2022) confirmed the relevance of background and upstream processes in metal supply chains due to their high share of indirect emissions. Moreover, our result that the role of co-mining is barely addressed (7.5% of studies) aligns with Watari et al. (2020), who recommended further research in this direction.

In line with our finding that results of prospective LCAs are highly diverse and challenging to compare, Watari et al. (2021) identified a high uncertainty in results of current literature for future metal demand, e.g. results differ by a factor of 2 or even more. Likewise, they explained these disparities by differences in methodologies and assumptions, and the complexity of models.

Lastly, similar to our study, many reviews voiced methodological challenges for the field of (prospective) LCA addressing, e.g., transparency and reproducibility of LCI data (Saavedra-Rubio et al. 2022; Laurent et al., 2014; Ghose 2024), unharmonized reporting (Picatoste et al., 2022), missing guidelines (Thoneman et al. 2020; Bisinella et al. 2021), incomparability of LCA results (Thoneman et al. 2020; Suh et al., 2004) and incomplete interpretations of scenario-based LCA results (Bisinella et al. 2021).

2.4.4. Limitations and future research

This study is subject to certain limitations. These lead to recommendations for future research which are complementary to the recommendations listed in Table 3 and section 2.4.2.

First, identifying the future impacts of a metal is not trivial, since many factors may influence the supply and demand systems in often interrelated ways. Existing studies estimated future impacts and investigated the consequences of certain developments. We aimed at providing an overview of this existing research by qualitatively reviewing their methods and results, focusing on impact trends and related scenario variables for each metal (section 2.3.2 – 2.3.3). However, we found that with such a qualitative assessment, no clear answer can be provided to the question of how future impacts might develop due to differences among metals, different scopes, modelling approaches, interlinked nature of variables, and limited insights into the respective studies. Thus, future research is needed for a quantitative assessment of future impact trends and drivers, which involves a harmonization of their models, scenario variables and storylines, to assess the impact trend of already modelled scenarios and effects of all variables in a single model.

Second, we reviewed studies which investigated prospective elements for determining future impacts of metal supply. We thus excluded studies which solely modelled prospective demand scenarios of metals and used constant impact intensities, such as Elshkaki (2019, 2020, 2021), Dong (2020), Elshkaki et al. (2020), or Guohua et al. (2021). As demand has proven a driving factor for future demand-related impacts, these excluded studies can provide valuable insights and data for future research on demand-related impacts of metal production.

Third, while this study reviewed scientific publications, non-scientific sources might also provide valuable information. Future review works might include more sources, e.g., white papers and technical reports.

Fourth, due to the choice of keywords for our search queries, certain developments might be excluded from this review, even though they might play a crucial role in the future for the supply of metals. These could include, for instance, increased urban mining, improved treatment of tailings or of end-of-life processes, such as new recycling methods for batteries. More research is needed especially for toxicity impacts of future metal supply, since mine tailings are known to be important contributors to global toxic emissions (Reinhard et al., 2019).

Fifth, literature reviews are by nature subject to publication bias, which emerges because negative results are less likely to be published than positive results. For instance, LCA studies about emerging technologies are more likely to be published if environmental impacts can be reduced, while technology developers may refrain from publishing the environmental impacts of economically attractive technologies if their environmental performance turns out unfavourable. Thus, the findings from Fig. 3 may be less robust than they appear.

Furthermore, while this review focused on the inventory modelling of LCAs, future developments can also be accounted for during the impact assessment, for example, through dynamic characterization factors for resource depletion impacts.

Moreover, a large number of LCA studies investigated the present environmental impacts of metal production (Bailey et al., 2021; Lee and Wen, 2017; Marx et al., 2018; Schulze et al., 2017; for example, on REE Sprecher et al., 2014; Vahidi et al., 2016). These studies were not evaluated in this work which focuses on future aspects of metal supply. Nevertheless, these static analyses may provide additional insights and data for developing metal scenarios.

Further, our analysis of modelling approaches and data sources cannot entirely capture the origin and dependency of different sources. Authors use different ways to cite data or describe modelling approaches, which we cannot fully detect. However, our analysis can reveal general patterns and recurrences. More detailed analyses are required to gain a full picture, e.g., using network theory.

Lastly, our analysis about adherence to FAIR data principles (section 2.3.5) is not extensive, since assessing the completeness of data is difficult and time-consuming. Therefore, we addressed the question via a keyword search and the manual elimination of false positives. Although this approach may not deliver exhaustive results, it can reveal a general lack of compliance with FAIR data principles.

Ultimately, we cannot offer a silver bullet to solve the problem of 1) publishing and documenting LCA data in a standardized format and 2) easily incorporating shared data. Steubing et al. (2023) provide an overview of current practices and propose possible improvements in this regard. Ghose (2024) discourages from publishing LCA data as supplementary information and instead recommends using repositories to best comply with FAIR data principles. Specifically, their assessment identified Zenodo as best suited repository provider. Solutions are needed for a more streamlined approach for the publication, documentation, and technical implementation of reusable scenario data for prospective LCAs.

While this review addresses future environmental impacts of metal supply, the metal industry is interlinked with all 17 sustainable development goals (IRP, 2020b; UNDP, 2016). Hence, more insights are needed concerning many aspects, such as geopolitical tensions and social sustainability (IRENA, 2023), governance (IRP, 2020b; Ali et al., 2017), resilience (Troll and Arndt, 2022), planetary limits (Schenker et al., 2022) or material constraints (Breyer et al., 2022; Schlichenmaier and Naegler, 2022; Liang et al., 2022; Ren et al., 2021; de Koning et al., 2018). As these topics require other methods than prospective LCA, they are beyond the scope of this study. Readers are thus referred to the related literature.

2.5. Conclusions

This study provides an overview of existing publications about future environmental impacts of metal supply. Our results reveal that demand-related impacts of future metal supply are likely to increase in the future due to a surging metal demand (for more details, see section 2.4.1 Key findings). Potential improvements on the supply side, such as renewable electricity or increased recycling shares, can reduce impacts per kg metal produced, but rising demand is likely to outstrip these gains. Our findings show that future research is needed to address more metals, impacts beyond GHG emissions and especially demand-related impacts of global metal markets.

Hence, to minimize future impacts, drastic measures along the entire life cycle are needed addressing both supply and demand. This requires comprehensive studies taking a systemic view of future demand, respective supply developments and the associated environmental impacts. It should involve not only the metal industry, but also related sectors, such as the energy system, and actors, such as policy-makers. The latter should aim at reducing demand and e.g., advancing recycling. Otherwise, not only climate goals but also objectives regarding land use change and ecosystem conservation might be threatened.

Identifying the future impacts of metal supply is not trivial, since many factors influence the supply and demand systems in interrelated manners. Thus, an efficient collaboration among researchers and all stakeholders is required. Yet, this is hindered by the currently prevailing research practices which we found to be characterized by insufficient publication of data, and untransparent and unharmonized documentation (see Table 3). Moreover, LCA models are at maximum reusable in isolation but not combinable to allow comparisons between studies.

We strongly recommend improving current research practices to facilitate collaborations and ultimately enable harmonized and more accurate assessments of scenario variables and interdependencies of sectors. The goal should be to combine scenarios from different sources to determine the overall impact trends, i.e., the joint effect of variables. Such a combination of variables requires improved guidelines and the publication of scenario data according to FAIR data principles. These recommendations could benefit not only metal scenarios, but prospective LCA in general.

The underlying data of our review is fully available at a repository (Harpprecht et al., 2023). It presents the impact trends, scenario variables, modelling approaches and respective data sources per variable, study and metal. Our study thus provides a take-off point for future research for a more sustainable metal supply.

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