Future environmental impacts of metals: findings from integrated scenario assessment with prospective LCA
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1 Introduction

1.1. Background

Metal production is not only energy-intensive and a major source of greenhouse gas (GHG) emissions, but also causes severe environmental impacts, such as land use, human toxicity, particulate matter emissions or ecosystem degradation (IRP, 2019; Nuss & Eckelman, 2014; Schenker et al., 2022).

About 10-17% of global GHG emissions and 12% of global human health impacts due to particulate matter emissions are caused by metal production (IRP, 2019). Historically, these impacts exhibited an increasing trend, driven by the continuously growing metal ore extraction of about 2.7%/year since 1970, among others (IRP, 2019). From 2000 to 2015 alone, metal production amounts almost doubled, as well as the associated GHG and particulate matter emissions. Likewise, related ecotoxicity and human toxicity impacts both increased by about 50% (IRP, 2019).

Among all metals, steel supply is with a share of 71% the major source of metal-related GHG emissions, followed by aluminium (11%), calcium (8.8%), copper (1.6%), gold (1.2%), titanium (1.2%) and zinc (1.1%) (Nuss & Eckelman, 2014). For human health and ecosystem damage, copper is the metal causing the highest impacts globally (Nuss & Eckelman, 2014).

The GHG emissions of steel production mainly originate from the energy-intensive process of pig iron production (Nuss & Eckelman, 2014) which is mainly operated with coal and coke. For copper, the mining process and especially treatment of sulfidic mining tailings are the dominating source of toxicity impacts.

Metal demand is expected to continue to grow for most metals, e.g., due to a growing population and a shift to metal-intensive low-carbon energy systems (de Koning et al., 2018; Schlichenmaier & Naegler, 2022; Watari et al., 2021). This poses significant challenges to climate and environmental goals, such as the Paris Agreement or the Sustainable Development Goals (IRP, 2020; Watari et al., 2023; Yokoi et al., 2022). From 2010 to 2050, global demand is expected to increase by 86% for steel and 140% for copper (Watari et al., 2021), with even steeper growth projected for minor metals like neodymium, dysprosium, cobalt or lithium—essential metals for low-carbon technologies like wind turbines or electric vehicles (Watari et al., 2020). Environmental impacts of metal production may thus rise substantially unless addressed by comprehensive measures (van der Voet et al., 2019).

Next to growing demand, metal supply and its associated environmental impacts are strongly influenced by numerous other future developments. Given the climate targets, production processes need to be adapted to drastically reduce their GHG emissions. Achieving a strong decarbonization requires the implementation of novel technologies, such as carbon capture and storage (CCS) (Chisalita et al., 2019), hydrogen-based or electrified processes (Lechtenböhmer et al., 2016). Switching to novel and decarbonized production technologies is especially required for steel production due to its high contribution to global GHG emissions, as discussed above. Climate goals will also lead to a decarbonized electricity supply, which can considerably decrease GHG intensity of potential electrified processes. Moreover, increased recycling shares and general energy efficiency improvements of processes can lower future impacts.

On the other hand, a potential decline in mined ore grades may intensify mining impacts, e.g., on human health and ecosystems, as lower ore grades reduce overall efficiency of mining processes. Such a decline has been reported for metals, such as copper, nickel and zinc, and may continue in the future depending on economic conditions for mine operators (Norgate & Haque, 2010).

The future environmental impacts of metal supply are thus uncertain and influenced by multiple, partly interrelated factors and also sectors, such as electricity supply.

This thesis is dedicated to the general question of how metal supply and its associated impacts may evolve in the future. Given the substantial climate relevance of steel production and the potential of declining mined ore grades to drive other, e.g., toxicity-related impacts, this research focuses particularly on these aspects.

1.2. An overview on the environmental impact assessment for metal production

1.2.1. Prospective LCA as a key method

Life cycle assessment (LCA) is probably the most powerful and commonly applied method to assess the environmental impacts associated with a product or product system over its entire lifetime, thus applying a systems perspective (ISO, 2006). It accounts for emissions from related sectors, e.g., from electricity supply or waste treatment processes, thereby considering sectoral interdependencies. As a process-based method, LCA can include parameters at a high granularity thus offering the possibility of considering a wide range of environmental and technological developments. Moreover, its impact assessment methods cover impact categories beyond climate change, such as particulate matter, human toxicity or land use, enabling a comprehensive assessment of impacts.

A common distinction in LCA models is between foreground (FG) and background (BG) systems. The FG system is typically created by the practitioner for the respective system under study and thus usually comprises a limited number of processes. In contrast, the BG system usually consists of thousands of processes to represent our highly interlinked economic system and its environmental interventions. It is therefore commonly sourced from a life cycle inventory (LCI) database, e.g., ecoinvent (Wernet et al., 2016). Such a BG database provides standard inputs to the foreground model, for instance, electricity or materials.

Prospective LCA (pLCA) is employed to analyze *future* technologies or systems by means of integrating scenarios. It enables the assessment of novel or immature technologies to guide technology design and development. Furthermore, it can also adopt a systemic perspective to investigate future production or market systems, such as the diffusion of new technologies into a market (Arvidsson et al., 2024; Arvidsson et al., 2017; van der Giesen et al., 2020). pLCA thus allows to evaluate future impacts of transformation pathways over time, e.g., of an energy transition with a shift to low-carbon technologies (Mendoza Beltran et al., 2018), and can thereby provide valuable insights for decision- and policy-makers.

pLCA applies the same four phases as conventional LCA, i.e., goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (ISO, 2006). As it additionally needs to account for scenarios in each phase, it is commonly structured into two main steps: *1) scenario generation* and *2) scenario evaluation* (Fukushima & Hirao, 2002). During scenario generation, scenario data is retrieved from literature, stakeholders, own calculations, or other sources, such as Integrated Assessment Models (IAM). Subsequently, scenario evaluation comprises the integration of the scenario data into the LCI database. The thereby created prospective LCI (pLCI) database is then used to conduct the four phases of a conventional LCA (goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (ISO, 2006)), while accounting for the additional dimension of scenario assumptions in each phase (Mendoza Beltran et al., 2018; Thonemann et al., 2020).

To achieve an internally coherent pLCA model representative of the future, scenarios should cover relevant sectors, e.g., metal and energy supply, and are preferably based on consistent assumption across sectors. Furthermore, scenarios are ideally integrated into both FG and BG system, to reflect future developments in both systems. This avoids a "temporal mismatch" between the assumed future FG system and the otherwise static BG LCI database (Arvidsson et al., 2017), as further explained below.

1.2.2. Prior research in prospective LCA of metal supply

At the time of writing, only a few studies investigated the future environmental impacts of metal supply at the global level (e.g., Hertwich et al., 2015; Kuipers et al., 2018; Ryberg et al., 2018). Most studies focus on individual metals (Kuipers et al., 2018; Ryberg et al., 2018), adopt partial scopes, such as specific production technologies or locations (e.g., (Chisalita et al., 2019; Khoo et al., 2017)), and apply diverse approaches and scenario assumptions. Additionally, many studies are characterized by insufficient transparency in reporting (Bisinella et al., 2021), making their findings difficult to compare. As a result, insights into the future impacts of metal supply based on systemic assessments remain limited. While comprehensive overviews of current environmental implications of metal production exist (Nuss & Eckelman, 2014; UNEP, 2013), they are lacking for future impacts.

The field of environmental impact assessment of future metal production was pioneered by van der Voet et al. (2019), who developed the first detailed global supply scenarios for seven major metals, including copper, nickel, zinc, lead, and iron. Their scenarios cover a wide range of relevant future developments or so-called scenario variables, such as ore grade decline, energy-efficiency improvements, and secondary production shares.

However, their methodological choices regarding consistency of scenario data and scenario integration suffer from certain limitations. For each variable, they use data from separate sources. Future ore grades, for instance, are estimated based on extrapolation of historic trends. Future electricity mixes are based on different energy scenarios from IEA (IEA, 2012) and manually incorporated as BG processes.

Most importantly, their future metal supply chains are not integrated in the background database but modeled in the foreground, "on top" of the background database. This approach creates a temporal mismatch between the FG and BG system, as all other processes of the BG database still make use of the non-future metal supply chains. This approach thus prevents a consistent assessment of interdependent sectors. Metal production, however, is closely interlinked with the energy system: it is highly energy-intensive, while low-carbon energy technologies are, in turn, characterized by a high metal-intensity. As a result, the future environmental performance of metal supply is not only influenced by processes within the metal sector itself but also by changes in the energy supply system—and vice versa. This bidirectional dependency is commonly referred to as the "energy-resource nexus" (Bleischwitz et al., 2017; Graedel & van der Voet, 2010; Le Blanc, 2015).

If metal scenarios are modelled in the FG system and not integrated into the BG database, interdependencies, as given by the energy-resource nexus, are not fully represented in the pLCA model. For example, photovoltaic (PV) panels generating electricity in 2050, e.g., for copper production in 2050, are then assumed as being manufactured using *today's* instead of *future* copper supply chains, resulting in temporal inconsistencies.

Mendoza Beltran et al. (2018) and later Sacchi et al. (2021) advanced this approach and developed tools to systematically integrate scenarios into an LCI database. First, they achieve consistency across scenario data as they use scenario data from one source for all sectors focusing on electricity and energy supply scenarios from IAMs, like IMAGE (Stehfest et al., 2014) or REMIND (Baumstark et al., 2021). Second, they integrate all scenarios directly into the BG database ecoinvent as so-called background scenarios thus generating one internally consistent pLCI database.

While these prior works incorporated detailed electricity scenarios from IAMs into a BG LCI database (Cox et al., 2018; Mendoza Beltran et al., 2018; Sacchi et al., 2021), comprehensive BG scenarios for metal production are so far lacking (Arvesen et al., 2018).

Few studies combined future electricity and metal supply scenarios within one LCI database as BG scenarios. However, they used by now outdated databases (ecoinvent version 1, or 2) and considered only one scenario variable for future metal production, namely energy efficiency improvements (Gibon et al., 2015; Hertwich et al., 2015). The library *premise* by Sacchi et al. (2021) includes BG scenarios for only one metal (steel) at the time of writing.

Information about future environmental impacts of metals is hence available, but in a fragmented and unharmonized manner, and based on diverging approaches. Since this thesis focuses in particular on potential declining ore grades and future steel production, as well as the methods for a more consistent scenario assessments via BG scenarios, these aspects will be further discussed. As illustrated above, LCA scenarios for declining ore grades exist (van der Voet et al., 2019), but they have not yet been incorporated as BG scenarios into an LCI database following an integrated, consistent approach to overcome a temporal mismatch between FG and BG database.

For future steel production, prior work has shown that emissions can only be sufficiently reduced by switching from conventional fossil-fuel-based production technologies to novel, e.g., electrified technologies (van der Voet et al., 2019; P. Wang et al., 2021; Yokoi et al., 2022). Promising alternative technologies are, for example, hydrogen-based direct reduction of iron (H2-DRI) (Zhang et al., 2021) or the less mature technology of electrowinning (EW), which uses electricity to reduce iron. Next to such (indirect) electrification of production, carbon capture and storage (CCS) can to some degree reduce direct emissions.

Previous assessments evaluated direct GHG emissions of the steel industry at national[1] or global scales[2], yet frequently neglected indirect emissions or other environmental impacts. However, indirect emissions, e.g., from electricity supply or hydrogen generation, are decisive for the overall emission intensity of novel technologies, like H2-DRI and EW (Bhaskar et al., 2020; Fischedick et al., 2014), which highlights the relevance of considering coherent multi-sectoral scenarios.

Only few studies assessed the environmental profiles per kilogram steel of some novel production technologies using LCA methodology, e.g., of CCS (Chisalita et al., 2019) or H2-DRI (Koroma et al., 2020; Li et al., 2022). These analyses revealed potential burden shifting to upstream supply chains or non-climate change impact categories, emphasizing the need for comprehensive life cycle assessments.

Although some studies evaluated future life cycle impacts of iron and steel supply in conjunction with scenarios for global demand, energy efficiency improvements and recycling shares, they neglected a shift to decarbonized steel production technologies. Moreover, their approaches suffer from inconsistencies as they use scenario data from disparate sources and did not integrate the metal scenarios into the BG database. Finally, they primarily assessed climate change impacts (P. Wang et al., 2021; Yokoi et al., 2022), apart from one study (van der Voet et al., 2019).

Thus, climate change impacts of the global steel market have been assessed on a per-kg-basis using scenarios from IAMs (Sacchi et al., 2021), e.g., IMAGE (Stehfest et al., 2014), but the assessments did not include novel steel production technologies, such as H2-DRI or EW, although these are required for a deep decarbonization of steel production. Research has yet to fully explore the environmental implications of future global steel production using multi-sectoral, internally consistent decarbonization scenarios while accounting for a broad range of emerging technologies and non-climate impacts.

1.3. Key challenges in prospective LCA of metal supply

1.3.1. The need for consistent scenario data and an *integrated* approach

Given the interdependencies between metal and energy systems, as described by the energy-resource nexus, assessing the future impacts of metal supply requires a systemic approach which can account for developments in related systems. The interlinkage of the metal and energy systems will gain in relevance under an energy transition requiring high capacities of low-carbon technologies and a simultaneous shift to a decarbonized, likely more electrified metal production. Next to energy technologies, the environmental per-

[1] for example for US: Rosner et al. (2023); Ryan et al. (2020), for DE: Arens et al. (2017); Harpprecht et al. (2022), for SW: Toktarova et al. (2020), or for CHN: Y. Wang et al. (2023).

[2] Lei et al. (2023); Speizer et al. (2023); van Ruijven et al. (2016); van Sluisveld et al. (2021); Watari et al. (2023); Xu et al. (2023)

formance of metal supply also considerably contributes to other sectors, such as buildings and construction (IEA, 2019; Reinhard et al., 2019).

However, the pLCA method described in Section 1.2.1, and as also illustrated by the description of the state of the art of pLCA for metals in Section 1.2.2, faces various challenges, which become even more prominent when considering scenarios for interrelated sectors (Mendoza Beltran et al., 2018).

For scenario generation, challenges relate to lacking and inconsistent background scenario data, specifically:

- a lack of scenario data for multiple sectors with global coverage and of sufficient technological, regional and temporal resolution from one, coherent data source;
- inconsistencies in assumptions and narratives across sectors, regions, and technologies especially when using scenario data from separate sources leading to unharmonized assumptions.

For scenario evaluation, challenges arise due to the technical complexity of integrating scenario data for interrelated sectors into LCI databases:

- The complex and interlinked nature of our economy is also reflected in LCI databases as they consist of several thousand processes. For instance, energy technologies require a variety of metals for their construction, while metal production processes consume energy generated from the new low-carbon energy system. The approach of incorporating scenarios for multiple, interdependent sectors needs to be able to account for that, such that the resulting pLCI database maintains the interlinkages, e.g., future metal production processes should source energy from future energy system and vice versa. If this applies, we here refer to an *integrated* approach.
- Another prevalent challenge in pLCA is the *temporal mismatch* between the FG and BG database, leading to inconsistencies of assumptions (Arvidsson et al., 2017). This applies when the FG system assumes future developments, while the BG system remains static, thus representing the present instead of the future. This is the case, for instance, when an original LCI database is used as the BG system for electricity generation while the FG system represents a future, decarbonized and electrified steel production. Updating the background database with so-called *background scenarios*, i.e., the integration of scenarios also into a BG LCI database, can resolve this issue. In practice, however, this task is complex due to the high number of processes and interlinkages in a BG database.

1.3.2. Challenges and outlook for solutions

The aforementioned challenges associated with prospective LCA can be summarized and addressed with the following methods.

1) Lacking and inconsistent background scenario data across relevant sectors (notably metal and energy supply):

To achieve high coherence of scenario assumptions across sectors, such as scenario narratives, regional, temporal and technological scopes, the scenario data ideally is retrieved from one instead of individual and fragmented sources.

Integrated assessment models are promising sources for internally coherent scenario data across multiple sectors accounting for interlinkages between sectors (Steubing et al., 2023). IAMs are global energy-economic-environmental models aiming at capturing the interactions between society, anthropogenic systems, and the environment (Pauliuk et al., 2017; Stehfest et al., 2014; van Vuuren et al., 2011). They are applied, for example, to develop cost-optimal decarbonization pathways for various sectors under varying socio-economic narratives (e.g., Shared Socioeconomic Pathways (SSPs)) and emission constraints (e.g., Representative Concentration Pathways (RCPs)) (O'Neill et al., 2014).

The usage of IAM data in pLCA has been pioneered by Mendoza Beltran et al. (2018), who applied regionalized electricity scenarios from the IAM of IMAGE for pLCA (Stehfest et al., 2014).

Although IAMs cover the most relevant energy sectors, such as electricity generation, they have a lower sectoral resolution than LCA and lack data for certain sub-sectors or parameters, such as production routes differentiated by metal or mined ore grades. In such cases, alternative data sources are required while aiming at consistency with scenarios for other sectors and scenario variables, e.g., retrieved from IAM models.

2) Technical complexity of integrating background scenario data for interrelated sectors in (p)LCI databases:

In recent years, various libraries have been developed to enable a consistent integration and combination of BG scenarios for pLCA. These libraries include *presamples* (Lesage et al., 2018), *Wurst* (Mutel & Vandepaer, 2017) and *premise* (Sacchi et al., 2021). They allow a systematic, automatized and reproducible integration of scenario data into both BG and FG LCI database while ensuring coherence of the newly generated database. They thereby enable an *integrated* approach and provide the technical means to resolve a temporal mismatch between BG and FG databases for pLCA.

Being from the first generation of these libraries*, presamples* can efficiently change amounts of existing flows in an LCA database based on precalculated values. *Wurst* and *premise* further extended these abilities as they can link and integrate scenarios from IAMs directly into a BG database, e.g., by adding LCIs for novel technologies, adapting and regionalizing supply chains and market mixes. They thereby allow to assess detailed multi-sectoral transformation pathways for entire sectors.

1.4. Problem statement and research questions

Metal production is associated with substantial environmental implications, which are likely to change in the future, e.g., driven by rising demand, declining ore grades, decarbonization measures, or an energy transition. In view of climate and environmental goals, it is key to identify the drivers and hotspots of future impacts caused by metal supply to effectively inform decision-making for impact mitigation. Comprehensive overviews of the future environmental implications of metal production are, however, currently lacking.

As metal production is closely interrelated with the energy sector, as described by the energy-resource nexus, assessing the future impacts of metal supply requires an integrated approach which can account for developments in interlinked sectors, like the energy supply. To achieve temporal consistency across sectors, such an integrated approach applies the principle of background scenarios and combines multi-sectoral scenarios into one LCI database.

Comprehensive background scenarios for crucial developments in metal supply are so far not available, such as mined ore grades and decarbonization pathways of steel production—despite the role of metal supply to other sectors, like infrastructure and low-carbon technologies in particular. Moreover, such metal supply scenarios have not been incorporated into a recent background database yet in conjunction with coherent electricity supply scenarios following an integrated approach and achieving consistency across sectors, as needed in light of the energy-resource nexus.

Hence, the main research question (RQ) of this thesis is:

> *How may the environmental profiles of metal supply evolve in the future, considering developments such as future ore grades or a decarbonization of steel production, as well as a consistent integration of scenarios for interrelated systems like electricity supply?*

This is guided by the following sub-questions:

1. *Which metals have been addressed by prior prospective LCA studies and what are their expected future impact trends as well as the main drivers of these impacts?*
2. *What are the future environmental impacts of supplying metals with declining ore grades, and can these be compensated by other developments, such as increased recycling or an electricity transition?*
3. *Which novel technologies and decarbonization pathways can achieve the highest CO_2 emission reduction for the iron and steel industry by 2050?*
4. *What are future environmental impacts of global steel production under consistent energy and steel supply scenarios, considering decarbonization pathways, future steel demand and impacts beyond climate change?*

It is important to note that this thesis primarily focuses on developments in metal production systems and may therefore rely on simplified assumptions for demand scenarios, a limitation discussed in Chapter 6.3.2.

1.5. Outline

Table 1 provides an overview of the structure and content of this thesis for chapters two to five, which each address one research question, respectively (RQ 1-4). This chapter (Chapter 1) introduces the overall background and research goal of this thesis. Chapter 6 provides the answers to each research question, and discusses the main contributions, outcomes, limitations as well as societal implications. The supplementary material for each chapter is available online, as specified in Annex A.

Table 1: Overview of the content chapters (Chapters 2-5) of this thesis regarding the respective metals covered, the methods applied, and the respective research question (RQ 1-4) addressed. Research questions are defined in Section 1.4.

	Content	Metals	Methods
2	· Literature review providing an overview of existing pLCA publications on future environmental impacts of metals. · Assesses their identified impact trends, and methods regarding scenario variables, data sources, scenario modelling approaches and integration.	Any	Systematic literature review
3	Assessment of the future environmental impacts of producing metals with declining ore grades, when combining BG scenarios for metal and electricity supply.	Cu, Ni, FeNi, Zn, Pb	pLCA per kg metal produced: · BG scenario generation for metal supply and ore grades; · BG scenario integration with *presamples* and *Wurst.*
4	· Identifies novel steel production technologies with the highest CO_2 emission reduction potential using a case study, i.e., steel decarbonization in Germany · Investigates the role of electricity supply scenarios and carbon budgets	Fe & steel	Developing process models of novel steel production technologies focusing on energy consumption and CO_2 emissions of future steel production in Germany of four decarbonization pathways.
5	Assessment of the future environmental impacts of global iron and steel production under consistent energy and steel supply scenarios from the IAM IMAGE, focusing on the effect of: · decarbonization pathways for steel including switching to novel technologies; · future steel demand; · comprehensive multi-sectoral BG scenarios.	Fe & steel	pLCA of novel steel production technologies and future global steel production: · develop LCIs of novel steel production technologies; · consistent BG scenario integration with *premise* for all scenarios.

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