Future environmental impacts of metals: findings from integrated scenario assessment with prospective LCA
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6 Discussion and Conclusions

6.1. Overview

Metal production is not only energy-intensive and a major source of greenhouse gas (GHG) emissions, but it is also associated with considerable other impacts, such as human toxicity or land use. Among all metals, steel supply is the major contributor to metal-related GHG emissions, while copper causes the highest impacts for human health and ecosystem damage, which especially occur during mining (Nuss & Eckelman, 2014). Given a growing population and the need for metal-intensive low-carbon technologies, metal demand is expected to rise in the future, which poses significant challenges to climate and environmental goals.

Next to demand growth, metal supply and its associated environmental impacts are likely to change in the future due to various, partly interrelated developments. Achieving climate targets will require a drastic decarbonization to reduce GHG emissions, particularly from steel production and electricity supply, which is crucial for lowering the GHG intensity of electrified processes. On the other hand, a potential decline in ore grades may intensify mining impacts, e.g., for copper or nickel.

This thesis aimed at assessing the future environmental impacts of metal supply focusing on the effects of future ore grades, decarbonization pathways of steel production and of developments in interrelated systems, especially electricity supply.

This work was structured into four research questions, which are examined in detail in Chapters 2 to 5, respectively. Table 1 provides an overview of the methods applied and main results per research question (RQ). First, we review existing studies on the future environmental impacts of metal supply and provide an overview of estimated impact trends, key drivers as well as of their methodological approaches (Chapter 2). Second, we assess the effect of potentially declining ore grades in combination with additional developments in metal supply, such as future recycling shares and electricity supply scenarios, via prospective LCA (Chapter 3). The fourth chapter identifies novel steel production technologies with the highest CO_2 emission reduction potential based on a case study, i.e., steel decarbonization in Germany, and highlights the relevance of accounting for interrelated sectors, like electricity supply. In the final chapter, we assess the future environmental impacts of global iron and steel production under multi-sectoral, internally consistent climate mitigation scenarios for energy and steel supply. The iron and steel scenarios consider nine steel production routes, including the introduction of novel technologies, technology-specific efficiency improvements, as well as region-specific recycling shares, production mixes and demand.

The following sections will summarize the key findings and contributions to the field of this work per research question to then answer the main research question (Section 6.2.5.). Section 6.3 discusses the limitations and suggestions for future research, while Section 6.4 reflects upon the findings and their implications.

Table 1: Overview of the methods and key results for each research question investigated in this thesis (Chapters 2-5). Further details are provided in Chapter 6.2.

Research question	Methods	Key results
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?	Systematic literature review	· 40 studies cover only **15 metals** and mostly bulk metals. · **Impacts per kg metal likely to decrease**, e.g., due to greener electricity, novel technologies or higher recycling shares. · **Absolute impacts may still increase** driven by rising metal demand.
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?	pLCA per kg of metal produced: · generated BG scenarios for metal supply for five variables: ore grade, technology mix, recycling shares, efficiency, production locations; · used BG electricity scenarios from IAM IMAGE; · integrated BG scenarios using *presamples* for metal and *Wurst* for electricity scenarios.	· **Most environmental impacts per kg metal produced are likely to decrease** despite declining ore grades for Cu, Ni, FeNi, Zn, and Pb. · Increased recycling shares and greener electricity supply can mostly compensate for the effect of declining ore grades.
3. Which novel technologies and decarbonization pathways can achieve the highest CO_2 emission reduction for the iron and steel industry?	Developing process models of current and novel steel production technologies assessing energy- and reaction-related CO_2 emissions using the case study of steel decarbonization in Germany: · developed and assessed 3 decarbonization scenarios for future steel production in DE considering novel technologies, efficiency, recycling shares, and furnace lifetimes. · time-dependent emission factors for electricity supply.	· **Electrified production technologies achieve highest CO_2 emission reduction**: up to 83% (H2-DRI), and 86% (EW). · Retrofitting existing BF-BOFs with CCS while simultaneously switching to electrified technologies, reduces cumulative CO_2 emissions of steel production in DE most effectively. · **All decarbonization scenarios exceed the sectoral carbon budgets** for the 1.5°C and 1.75°C target by 2050 under constant steel production.
4. What are the 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?	pLCA of novel steel production technologies and future global steel production: · All multi-sectoral scenarios are sourced from one IAM (IMAGE) (electricity, steel, and other energy sectors) and integrated as BG scenarios using *premise.* · developed LCIs of novel steel production technologies, including CCS, hydrogen-based or electrified processes.	· **Reaching net-zero steel production is unlikely** as GHG emissions per kg steel decrease by max. 79% by 2060. · **Decarbonization may shift burdens** from climate change to other impact categories, e.g., driven by upstream supply sectors, like electricity supply. · **Steel production is likely to require large shares of global carbon budgets of up to 30%** even under the most optimistic decarbonization scenario.

6.2. Key findings and contributions

This thesis assessed the trends and drivers of future environmental impacts of metals. Methodologically, the goal of this thesis was to contribute to a more consistent assessment of multi-sectoral scenarios in pLCA, specifically by 1) generating background scenarios for global metal supply suitable for prospective LCA for crucial developments, such as future ore grade decline and a decarbonization of steel supply; and 2) enabling a more consistent combination of multi-sectoral background scenarios for interlinked sectors, such as metal and electricity supply, in (p)LCI databases.

6.2.1. Future environmental impacts of metals: insights, knowledge gaps and emerging challenges

RQ 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?*

To answer this question, we conducted a systematic literature review of existing publications which assessed future environmental impacts of metal supply. We evaluated their results regarding impact trends and drivers, as well as their methods regarding scenario variables, data sources, scenario modelling approaches and integration.

The results show that the future impacts of metals are so far insufficiently addressed by existing research. Our review identified 40 publications; however, these studies cover only 15 metals (copper, iron, aluminium, nickel, zinc, lead, cobalt, lithium, gold, manganese, neodymium, dysprosium, praseodymium, terbium, and titanium). The majority of publications focuses on major metals, like copper, iron and steel, or aluminium. There is a lack of studies on the impacts of metals which are crucial for the energy transition, e.g., lithium, cobalt or neodymium, and of metals with substantial global production impacts, e.g., calcium, magnesium, or silver.

Moreover, we found that knowledge on future impacts beyond climate change, such as land use or human toxicity, and on impacts at a global scale, i.e., accounting for future global metal demand, is lacking, since most studies assess GHG emissions or impacts per kg metal produced. There is a lack of studies on future absolute impacts, i.e., considering future metal demand.

Regarding impact trends, our results reveal 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, another key driver. Thus, future demand-related impacts are still likely to increase.

The ultimate impacts remain unclear due to highly heterogeneous and inconsistent research scopes, scenario assumptions and narratives, which determine impact results. 229 unique data sources were identified for 15 scenario variables.

6.2.2. The effect of future mined ore grades in light of the energy-resource nexus

RQ 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?*

In response to this question, we conducted a prospective LCA study for metals which a decline in mined ore grades has been documented for. These are copper, nickel, ferronickel, zinc and lead. Specifically, we developed metal supply scenarios for these metals and combined them with two electricity supply scenarios from IMAGE as background scenarios into the BG database ecoinvent using the Python libraries *presamples* and *Wurst* respectively. The metal scenarios describe five future developments: mined ore grades, primary production locations, energy-efficiency improvements, technology mix for primary production, and shares of primary and secondary production.

Our results reveal that for the assessed metals most environmental impacts are likely to decrease per kg metal supplied despite a decline in mined ore grades. Increased recycling shares and greener electricity supply can to a large extent compensate for the effect of declining ore grades.

Considering both metal and electricity scenarios has proven essential as they drive impacts in different categories. Climate change impacts can be reduced by using greener electricity, while, for example, human toxicity can most effectively be lowered by improving mining or metal production processes. This study thus demonstrates that reducing impacts beyond climate change requires not only greener electricity but also targeted emission mitigation measures for metal production processes.

An assessment of the future impacts of low-carbon technologies crucial for the energy transition (e.g., PV power generation or lithium-ion battery production) reveals very similar patterns under our background scenarios: Their climate change impacts can be considerably decreased by switching to greener electricity, while impacts like human toxicity and metal depletion can most efficiently be lowered by improving metal production.

This study thus demonstrates the interdependency of the energy and metal supply sectors: future metal supply impacts influence impacts of future energy supply, and vice versa, highlighting the relevance of consistent multi-sectoral scenarios in future impact assessments.

6.2.3. Novel technologies and transition pathways for a decarbonization of iron and steel production

RQ 3: *Which novel technologies and decarbonization pathways can achieve the highest CO_2 emission reduction for the iron and steel industry?*

Given the high GHG emission intensity of the iron and steel production and the need for its decarbonization to comply with climate targets, we assessed the CO_2 emission reduction potential of novel iron and steel production technologies. This work was conducted with a case study focusing on steel decarbonization in Germany, which is the largest steel producer in Europe and ranks seventh worldwide. We developed bottom-up process models of current and four promising alternative steel production routes accounting for process-specific energy requirements as well as energy- and reaction-related CO_2 emissions. The role of background electricity supply was assessed using time-dependent emission factors of the future electricity mix in Germany. Furthermore, we developed three decarbonization pathways for steel production in Germany until 2050 to evaluate the diffusion of those emerging technologies considering technology maturity, age and lifetimes of existing furnaces, and recycling shares, among others.

We found that electrified production technologies have the highest CO_2 emission reduction potential if power is decarbonized: up to 83% for hydrogen-based direct reduction (H2-DRI), 86% for electrowinning (EW) and 90% for steel recycling (scrap-EAF) compared to the currently coal-based blast furnace and basic oxygen furnace (BF-BOF) route. Carbon capture and storage (BF-BOF-CCS), reduces CO_2 emission by only 50%.

Although the reduction of annual CO_2 emissions by 2050 were very similar across decarbonization pathways (72–83% relative to 2020), their cumulative emission reduction by 2050 differed considerably: ranging from 24% to 46% compared to the reference scenario (under constant steel production). The lowest cumulative emissions were achieved when retrofitting existing BF-BOFs with CCS while simultaneously switching to electrified technologies. We hence demonstrated that the technology pathway, i.e., the implementation speed and choice of alternative technologies, is decisive. Moreover, the results revealed that green power is key to realize the emission benefits of electrified and hydrogen-based technologies: it can further reduce cumulative CO_2 emissions by 12% by 2050 (i.e., by 128 Mt CO_2).

All decarbonization scenarios considerably exceed the sectoral carbon budgets for the 1.5°C and the 1.75°C target for the German steel industry by up to a factor of almost five, despite an assumed constant steel production. Even our most optimistic scenario would exceed the sectoral 1.5°C budget in the 2030s, underscoring that it will be a race against time to implement more drastic and additional measures to limit emissions in the future.

Our analysis further reveals major consequences of decarbonizing steel supply for the energy sector regarding capacity requirements for renewable electricity, electrolyzers, and CO_2 storage. For instance, electricity demand would rise 15-fold by 2050 (to 81 TWh/year), which would, for example, translate into additional 150% of currently installed PV capacity in Germany.

This work thus highlighted the need for more detailed assessments of the future emissions of steel production, considering i) the market diffusion of novel, including electrified and CCS-related, technologies; ii) scenarios in upstream sectors, e.g., energy supply; and iii) future steel demand. Building on this case study, the environmental implications of steel production at the global level were explored in the following study which accounts for life-cycle-based emissions and uses internally consistent scenarios for global steel and energy production with a high technological and spatial resolution.

6.2.4. Future environmental impacts of global iron and steel production

RQ 4: *What are the 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?*

This question was investigated with a pLCA study. The unique features of this work were: i) we used multi-sectoral and internally consistent scenarios, as they are all sourced from one IAM, i.e., IMAGE; ii) the steel scenarios from IMAGE account for the adoption of novel production technologies, such as carbon capture and storage (CCS), hydrogen-based or electrified processes; and iii) the detailed, regionalized steel production scenarios were combined with coherent energy scenarios into a pLCI database for three climate mitigation pathways using the Python library *premise*. This integrated approach enabled a comprehensive assessment of the future environmental impacts of global steel production providing a supply chain-based overview for a wide range of impact categories across various world regions for three climate mitigation pathways: a 3.5°C baseline, a <2°C and a 1.5°C target.

We found that electrified steel production technologies, both directly and indirectly powered, offer the highest GHG reduction potential achieving up to 95% by 2060 compared to current coke-based processes, provided that decarbonized electricity is utilized. They thereby clearly outperform CCS technologies for coke-based processes. Yet, even if transitioning to a much more electrified steel production by 2060 as in the ambitious 1.5°C scenario, it is unlikely that global steel production will realize the net-zero target, since GHG emissions per kg steel decrease by max. 79% by 2060.

Considering future steel demand growth revealed that global steel production could consume considerable shares of global carbon budgets even under the most optimistic scenario, i.e., up to 30% of the global end-of-the-century 1.5°C carbon budget by 2060.

Moreover, our analysis demonstrated that decarbonization measures could shift burdens from climate change to other impact categories, such as ionizing radiation or land use. Impacts of the global steel production globally may rise in most categories, as they decline only for GHG emissions, and to a lesser extent in acidification, freshwater eutrophication, particulate matter, and photochemical ozone formation.

These rising impacts largely depend on upstream and downstream sectors, especially the electricity mix, but also metal mining, or waste treatment processes. When switching to novel production technologies, emission hotspots will shift away from the direct steel production (like blast furnaces) to indirect sources, e.g., electricity and hydrogen supply for H2-DRI and electrowinning.

Overall, this study highlights that system-wide strategies are required to reduce both climate and non-climate impacts of steel production more drastically than assumed in our scenarios to meet climate goals. These include demand reduction, increased recycling, accelerated decommissioning of coke-based furnaces, a faster ramp up of electrified steel production and renewable electricity generation capacities, as well as implementing targeted, process- and impact-category-specific emission mitigation measures along the entire supply chain to avoid burden-shifting. Multi-sectoral scenarios and a life-cycle-based approach as applied in this study are hence crucial to identify solutions.

6.2.5. Main research question

The findings of the four sub-research question allow to answer the main research question of this work:

> *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?*

We found that life cycle impacts on a per-kilogram-basis are likely to decrease for most metals and impact categories. Key drivers for these reductions are a greener electricity supply, increased recycling shares, and switching to novel, decarbonized production technologies (Chapters 2-5). For steel production, GHG emissions are most effectively reduced with electrified or hydrogen-based production technologies, provided that decarbonized electricity is used. Nevertheless, these do not achieve climate-neutrality from a life cycle perspective. Realizing net-zero steel production by 2060 is thus unlikely even under the most optimistic scenario (Chapter 5). A decline in mined ore grades, as expected for copper, nickel, ferronickel, zinc, and lead, may increase impacts per kg—yet, this effect can largely be compensated by other improvements, such as the aforementioned greener electricity supply and increased recycling shares (Chapter 3).

However, emission reductions per kg of metal produced may be insufficient to fully compensate for the effect of growing global metal demand. As a result, demand-related impacts are still likely to rise for many metals across several impact categories (Chapters 2 and 5). This trend was also identified for iron and steel production, where global demand growth leads to increasing impacts in most categories. Meeting climate targets in this sector will be particularly challenging, as it may require disproportionately large shares of the remaining carbon budgets by 2060—both at a global and national level, e.g., in Germany. Absolute GHG emissions at the global level may even increase by 2060, unless currently fossil-fuel-based production technologies are continuously phased-out (Chapters 4-5).

While decarbonization measures are imperative to reduce climate change impacts, they can shift burdens to certain impact categories on a per-kg-basis, such as ionizing radiation, metal depletion or land use. These adverse side-effects are largely—though not solely—caused by electricity supply and higher electricity requirements for future electrified production technologies, as well as by waste treatment or chemical production processes (Chapter 5).

The hotspots of metal supply impacts largely depend on the impact category, which means that targeted process-specific interventions throughout the entire life cycle are required to avoid a rise in associated environmental impacts. While a greener electricity supply and decarbonized production technologies can reduce climate change impacts, negative side-effects in other impact categories may occur which require process-specific mitigation measures.

6.2.6. Methodological contributions

Next to highlighting strategies to reduce impacts of metal production, this thesis contributes to addressing methodological challenges associated with pLCA, as outlined in the introduction (Chapters 1.2-1.3).

With respect to the first challenge of lacking background scenario data of high consistency for metal and energy supply, we made two contributions. First, **we provided a systematic overview of metal scenarios available in the literature** (Chapter 2) specifying scenario variables, modelling approaches and respective data sources, as well as future impact trends. Openly published in a repository, this creates a knowledge database of the state-of-the-art of impact assessment of metal supply and thus facilitates future scenario evaluations. Second, **we generated background scenarios for global metal supply for several metals covering two crucial developments, i.e., future ore grade decline** (Chapter 3)**, and detailed decarbonization pathways of steel supply** which are consistent with energy scenarios (Chapter 5). Next to a shift to novel decarbonized technologies, our scenarios consider other relevant developments, e.g., recycling shares, regional production mixes, or energy efficiency improvements. This work thus provided the first comprehensive background scenarios for metal supply and expands the existing body of background scenarios from the electricity (Cox et al., 2018; Mendoza Beltran et al., 2018; Sacchi et al., 2021) to the metal supply sector.

With respect to the second challenge, i.e., integrating background scenario data for interrelated sectors into (p)LCI databases, **we applied and contributed to the development of cutting-edge tools enabling this integration,** like *presamples* and *premise*—a previously complex and obstructive step. We thereby achieved a consistent integration and combination of the metal supply scenarios with electricity scenarios into one internally consistent pLCI database. This *integrated* approach is essential to create an LCA model which can coherently represent future systems considering scenarios for interlinked societal sectors. It not only makes it technically easier to identify environmental hotspots and demand-related impacts of future systems, but also enables a more accurate assessment which revealed key insights, such as:

- Life cycle GHG emissions of future global steel production are likely to exceed sectoral carbon budgets even under a shift to electrified production and greener electricity.
- The potential trade-offs of electrifying steel production, e.g., caused by a future decarbonized electricity supply (Chapter 5).
- The joint, including downstream, effects of electricity and metal supply changes: metal supply improvements can enhance the GHG reductions of greener electricity, and lower human toxicity and metal depletion impacts, e.g., of low-carbon energy technologies (Chapter 3).
- The need for measures across supply chains: a greener electricity lowers GHG emissions, but other impacts, like human toxicity, ecotoxicity or ionizing radiation, require interventions directly at mining and metal production processes (Chapters 2-5).

Ultimately, this work provides an example of scenario generation and evaluation for detailed BG scenarios that can be applied to other sectors, thereby offering guidance for reducing environmental implications of other production and economic systems. To facilitate such future studies, all underlying (non-proprietary) scenario data, LCIs, and the Python code are made available in open access repositories (Table 2). We thus contribute to more transparent, reproducible, collaborative, and open research. As the energy and steel scenarios are suitable for *premise*, they can easily be reused or adapted.

Table 2: Links to scenario data generated and Python code for each chapter. Scenario data is published within the limits of proprietary data of ecoinvent.

Chapter	Data and Python Code
2	Supplementary data for the article: Future environmental impacts of metals: a systematic review of impact trends, modelling approaches, and challenges
3	Scenario data for article: Environmental impacts of key metals' supply and low-carbon technologies are likely to decrease in the future
4	Supplementary data and code for article: Decarbonization scenarios for the iron and steel industry in context of a sectoral carbon budget: Germany as a case study
5	Code and data for publication: Future Environmental Impacts of Global Iron and Steel Production

6.3. Limitations and recommendations

This section discusses the limitations associated with this work and suggests recommendations for future research.

6.3.1. Recommendations for future and more integrated quantitative assessments

The literature review in Chapter 2 aimed at identifying scientific publications with prospective elements in their LCA models. It hence excluded non-scientific publications, studies on present impacts or on future metal demand. Future research could include these publications to improve the data basis of the review. While this probably won't affect the main conclusions, e.g., that future environmental impacts of metals are likely to increase, these additional studies provide valuable data for future research, e.g., to couple metal demand scenarios with pLCA models to quantify demand-related impacts.

Furthermore, the overview of future impacts of metals presented in Chapter 2 was based on a qualitative review of impact trends identified in existing research, since a quantitative evaluation was hindered by the studies': i) high diversity of scopes and assumptions; ii) lacking or untransparent publication of (scenario) data; and iii) diverse documentation and data formats. While our qualitative analysis was sufficient to identify a likely increase in future impacts due to rising metal demand, quantitative assessments could deepen the knowledge of impact scales, underlying drivers, and mitigation measures.

Our review identified knowledge gaps and methodological shortcomings. Based on these, we derived recommendations to advance future research on metal supply assessments and pLCA in general. These include:

- More prospective LCAs on additional metals are needed to better understand their future impacts. Future research could prioritize metals with (see Chapter 2.3.1):
    - currently high contributions to global GHG emissions (e.g., calcium, magnesium, or chromium) or to ecosystem and human health impacts (e.g., molybdenum, mercury, uranium, or platinum);
    - expected drastic demand growth (see e.g., Watari et al., 2020, 2021);
    - high relevance for the energy transition (e.g., lithium, cobalt, dysprosium, neodymium, or nickel (Schlichenmaier & Naegler, 2022).
- Future studies ideally account for:
    - key drivers, such as novel production technologies, and related sectors, like electricity supply;
    - demand and supply scenarios, using consistent assumptions and multi-sectoral scenarios;
    - impacts beyond GHG emissions.
- Research practices should be improved and aligned towards:
    - a harmonization of models regarding scopes, scenario variables, and narratives using common and well-documented storylines like SSPs;
    - a standardization of scenario data and documentation formats to enhance accessibility and reusability, ideally adhering to FAIR data principles.

These recommendations guided our multi-sectoral studies, which combine metal and energy supply scenarios (Chapters 3-5). While our work covers selected metals, namely the GHG-intensive steel production (Chapter 4-5) and those potentially affected by declining ore grades, i.e., copper, nickel, zinc, and lead (Chapter 3), future research is needed to address additional metals. Given the large number of relevant metals, this task requires a coordinated community effort. The harmonization of models and methods, as well as adherence to FAIR data principles are thus essential.

6.3.2. Enhancements of LCI models and alternative scenarios

The pLCA models and scenarios presented in this work are subject to certain limitations and data gaps. Thus, the data basis of our LCI models and scenarios could be refined by accounting for additional factors, as illustrated by the examples in Table 3. Further recommendations are provided in the detailed discussion sections of the respective Chapters.

In particular alternative demand scenarios could provide valuable insights, as this work focused on supply-side developments. Demand scenarios were thus based on existing scientific literature suggesting continuous steel production levels in Germany (Chapter 4) or were sourced from established models, such as IMAGE, which foresees increasing steel production globally, e.g., due to expanding economies in Africa or India (Chapter 5). A comprehensive review of scientific scenarios confirms that steel demand is likely to increase globally by 2050 (Watari et al., 2021). However, since demand is a key driver of environmental impacts, the results should be interpreted in view of the limited demand scenarios considered in this work.

A simplified sensitivity analysis in Annex B estimates the effects of lower steel demand for Chapters 4 and 5, for instance through drastic demand-side measures. It confirms the main conclusion that the steel industry is likely to consume disproportionately large shares of the remaining 1.5°C carbon budgets. Some scenarios nearly meet the 1.75°C budget for Germany and the global 2°C budget by 2050 and 2060, respectively, although full compliance by 2100 remains highly challenging even under these optimistic demand assumptions (see Annex B).

An extensive body of literature (e.g., as presented by Creutzig et al., 2024; Hertwich et al., 2019; Watari et al., 2021) has emphasized the relevance of demand-side solutions offering valuable insights that can complement the analyses performed in this work. Some studies assessed the combination of supply-side and demand-side strategies for material systems, e.g., for steel and construction metals (Milford et al., 2013; Zhong et al., 2021). Likewise, these studies found that supply-side measures alone are insufficient to comply with climate targets. They stress that substantial emission reductions can only be achieved under additional material efficiency strategies that lower future demand, such as reducing floorspace, implementing lightweight design, or extending lifetimes of buildings and products (Hertwich et al., 2019; Milford et al., 2013; Zhong et al., 2021). Nevertheless, they found that even with all supply- and demand-side measures combined the 1.5°C budget is likely to be exceeded by 2060 and adhering to the 2°C budget by 2100 remains highly challenging (Zhong et al., 2021).

At present, integrated assessment models, like IMAGE, lack the capacity to fully represent material demand accounting for interdependencies across sectors (Creutzig et al., 2024). A consistent assessment of the environmental impacts of comprehensive supply- and demand-side scenarios thus requires advanced modelling frameworks that can consistently couple material demand and supply systems. Developing such framework lies beyond the scope of this work and thus constitutes an important direction for future research.

Table 3: Suggestions for future research to investigate additional factors or scenarios, including a discussion of their potential effect on the outcomes, i.e., the estimated future environmental impacts of metal.

Factor	Explanation	Effect on outcomes
Alternative scenarios	Our scenarios are *exploratory*, i.e., *what-if* scenarios (Chapter 3-5). They provide insights into potential future developments and their consequences, but no predictions. Expanding the scope of the scenarios across sectors by integrating other modelling frameworks, e.g., offering higher technological, spatial, or economic resolution, can yield further, more detailed insights (see suggestions below).	The effect can be potentially very large, e.g., if key drivers, such as demand, electricity or technology mixes, change considerably, or additional drivers are identified.
Demand	1. Chapter 3 assessed impacts for metals with declining ore grades (Cu, Ni, Zn, Pb) on a per-kg basis but excluded demand-related impacts. 2. This was resolved in Chapter 5 for steel with regionalized steel demand, though on an aggregated level, e.g., lacking scenarios specific for steel types, such as chromium or alloy steel. Alloying elements can considerably increase impacts of steel types. Moreover, material efficiency strategies were not explicitly considered, despite their high emission reduction potential (Zhong et al., 2021).	Very drastic demand reductions are required to achieve overall decreasing instead of increasing impacts. 1. Demand is expected to increase also for Cu, Ni, Zn, Pb (Watari et al., 2021). Including demand complements the analysis but is unlikely to change our result from Chapter 2 that demand-related impacts are likely to increase, which is in line with results from Yokoi et al. (2022). 2. More detailed steel demand scenarios can considerably affect overall impacts and potentially hot-spots.
Technological innovations	Novel technologies are accounted for to a limited extent. Chapter 3 did not consider low-carbon technologies for producing Cu, Ni, Zn, or Pb, but only for electricity supply. This was further refined in Chapters 4 and 5 which account for low-carbon technologies for steel production, with Chapter 5 including new technologies also for other sectors, like energy, transport, and cement.	As the hotspots highly depend on the impact category, the effect of novel technologies cannot be generalized. For GHG emissions from steel production, more significant reductions than for EW and recycling are unlikely, although they may be substantial for other metals. For non-climate impacts, novel technologies along the supply chain, e.g., aiming at electrification or pollution control, can have substantial effects.
Developments in other sectors and supply stages	This work revealed the relevance of considering multi-sectoral scenarios. Chapter 3 and 4 combined metal and electricity supply scenarios. Chapter 5 included scenarios for additional energy and energy-intensive sectors. Further scenarios are needed for sectors of high contributions, such as heat supply, chemical production, alloying elements, or waste treatment processes for tailings and slag, to extend the scope of sectors considered.	

Consistency across multi-sectoral scenarios	Our metal scenarios developed in Chapter 3 and 4 are not internally consistent with the used electricity scenarios due to lack of data from one source, e.g., for Cu, Ni, Zn, or Pb production in IMAGE. The developed LCA scenarios for metal production could be used to better represent the metal production sectors in larger integrated models, e.g., IAMs.	We tried to achieve suitable matches between the narratives of the sourced scenarios. For climate change, the main driver was electricity supply. Sophisticated demand-driven ore grade scenarios are non-trivial and subject for future research.
Regionalization of LCI and scenario data	Industrial production and mining processes are highly diverse across regions. While we aimed at accounting for regionalization in our models, this could be enhanced by incorporating region- and site-specific production conditions, e.g., for ore grades, chemical usages, or waste treatments.	Region-specific assessments enable a comparison and localization of impacts, as well as the design of region-specific mitigation measures.

6.3.3. Relevance of environmental trade-offs remains uncertain

In Chapter 5, we found that decarbonizing steel production may shift burdens to non-climate impact categories, such as land use, material resource depletion, and ionizing radiation. Results from normalization and weighting suggest that non-climate impacts may gain in relevance in the future—a concern that has been voiced by prior work on metal production impacts (Giljum et al., 2025; Schenker et al., 2022; Watari et al., 2021). Moreover, some impact categories, e.g., water use or chemical pollution, affect ecosystems and human health primarily at the local level, which cannot be evaluated with the models used here.

The relevance of these trade-offs remains, however, uncertain due to limitations in normalization and weighting methodologies (Pizzol et al., 2017). We thus recommend further research to assess the relevance of different impact category at both regional and global levels, e.g., using frameworks like planetary boundaries (Schenker et al., 2022; Steffen et al., 2015) or regionalized impact assessment (Hellweg et al., 2023), as well as defining and allocating respective impact threshold to guide sustainability evaluations.

6.3.4. Comprehensive frameworks for guiding sustainable transitions

While this works identified key technologies and strategies to lower the future environmental impacts of metal production, realizing a truly sustainable metal supply requires addressing a broader set of issues (UNDP, 2016), such as ecosystem conservation (Sonter et al., 2018), social equity (IRENA, 2023), economic development (UNDP, 2016), geopolitics (IRENA, 2023), or resilience (Troll & Arndt, 2022). Furthermore, establishing internationally coherent governance frameworks and policy strategies is essential to incentivize the adoption of sustainable practices across the global supply chain and to prevent the relocation of production to regions with weaker regulatory standards (Giljum et al., 2025; IRP, 2020). However, these topics require methods beyond the scope of prospective LCA. We therefore recommend further research to complement this work, using comprehensive frameworks which can address these additional dimensions and thereby support the transition to a more sustainable metal supply.

6.4. Reflections and implications

This research offers valuable findings to inform industry and policy-makers in designing effective strategies to reduce the climate and non-climate impacts of metal production in the future.

6.4.1. Greenhouse gas emissions

Climate-neutral metal production unlikely even for best-performing technologies

Even though technological solutions exist to considerably reduce the GHG footprint of primary and secondary metal production, we found that they do not achieve climate-neutral production from a life cycle perspective (Chapters 2-5). For instance, steel production technologies with the highest GHG emission reduction potential (up to 95%), i.e., the electrified technologies like EW and scrap-EAF, still have remaining emissions of 0.12 kg CO_2-eq./kg steel by 2060. These originate from fuel and material inputs, as well as direct reaction-related emissions from EAFs. Likewise, CCS technologies cannot achieve net-zero life cycle emissions, although they are often appraised as a promising solution, e.g., by steel producers.

Hence, even if production were to shift entirely to the best-performing technologies, additional strategies will still be required to mitigate residual emissions, such as Direct Air Carbon Capture and Storage (DACCS) or natural sinks. Their future capacities are, however, limited (Mengis et al., 2022), and environmental benefits of DACCS strongly depend on system configurations (Terlouw et al., 2021).

For steel production specifically, deploying CCS to coke-based plants poses the risk of a lock-in effect, as the emission reduction potential of CCS is insufficient in the long-term and may thus delay the transition to production of lower emission intensity. It is thus crucial to prioritize other technologies and mitigation strategies, including demand-side solutions, to minimize the need for CCS capacities for BF-BOFs (Creutzig et al., 2024). While similar conclusions have been drawn for other sectors, like hydrogen generation (Wei et al., 2024), they cannot be generalized to all hard-to-abate sectors. For cement production, for instance, CCS may remain necessary due to unavoidable process emissions and a lack of better, readily available solutions (Müller et al., 2024).

Faster action and lower demand needed in light of remaining carbon budgets

Our results show that GHG emissions caused by metal production may decrease insufficiently to comply with climate targets or may even increase unless demand is reduced and drastic measures are taken (Chapters 2-5). Steel production alone, the metal with by far the highest GHG intensity, may consume a substantial share of the remaining carbon budget—up to 30% for the 1.5°C scenario and 14% for the 2°C scenario by 2060, a conclusion in line with previous research for steel and other major metals (Harpprecht et al., 2022; Wang et al., 2021; Yokoi et al., 2022), as well as other hard-to-abate sectors, such as cement (Müller et al., 2024) or global building material production (Zhong et al., 2021).

To the best of our knowledge, our work in Chapter 5 represents the first quantification of life cycle emissions of global steel production considering a transition to novel production technologies, a knowledge gap often voiced by prior research (van der Voet et al., 2019; Yokoi et al., 2022). This revealed that i) switching to low-emission production technologies does not resolve the issue if overall and especially primary production amounts continue growing; ii) neither the steel nor the cement sector achieve net-zero emissions by 2060 and thus will claim additional portions of the remaining carbon budget beyond this timeframe. Our results thus highlight that the major industrial sources of greenhouse gas emissions (metal and cement production) are likely to threaten climate goals unless demand will be reduced, production transformed even more rapidly and drastically, and residual emissions mitigated by additional sinks.

Broad portfolio of system-wide measures required to speed-up emission reduction

Not only faster technological development and large-scale implementation of green technologies but a wider portfolio of measures are needed to sufficiently limit future GHG emissions. Additional strategies should be both production- and consumption-oriented and aim at:

- Reducing demand and especially primary production, particularly for emission-intensive production routes, through means as a circular economy, material substitution, or by increasing lifetimes and material efficiencies (Zhong et al., 2021);
- Promoting and facilitating recycling while simultaneously expanding capacities for secondary metal production, such as scrap-EAFs for steel in the future, which later can be used to refine iron from H2-DRI and EW;
- Supporting a faster commercialization and deployment of innovative technologies, like EW or H2-DRI, e.g., via investments, subsidies, and research funding;
- Ramping up the supply infrastructure for renewable electricity and green hydrogen, which are both likely to be limiting resources (Watari et al., 2023; Watari & McLellan, 2024);
- Specifically for steel, the phase-out of emission-intensive facilities for primary production BF-BOFs, and their replacement with NG-DRI should be accelerated. NG-DRI is a mature technology of lower emission intensity than BF-BOFs and can switch to near zero-emission H2-DRI when sufficient green hydrogen becomes available, which avoids the lock-in effects of CCS described above; and
- Generally, the use of high ore grades, green electricity and hydrogen should be incentivized.

Financial incentives will be necessary to overcome the economic barriers associated with these strategies, including high investment and energy costs, e.g., for hydrogen, natural gas or green electricity. The metal production sector is highly price competitive at an international level which poses a significant challenge to its transformation and makes economic support, policies and regulations imperative to incentivize its costly transition. An example of such a supporting framework is the European Clean Industrial Deal, which aims at making decarbonized production more profitable, e.g., by providing funding opportunities, promoting circular economy measures, or boosting demand for clean products through LCA-based product labels (European Commission, 2025).

6.4.2. Environmental impacts beyond climate change

Impacts of metals are likely to increase in many non-climate categories

Next to GHG emissions, non-climate environmental impacts associated with metal production exhibited an increasing trend in the past, such as particulate matter or toxicity, which can be partly attributed to rising ore extraction (IRP, 2019). Our results suggest that, to a large extent, this trend may continue driven by continuing demand growth, although exceptions apply (Chapters 2, 5). Thus, no absolute decoupling can be expected.

Environmental co-benefits of GHG reduction and decarbonization measures

Similar to GHG emissions, many non-climate impacts of metal production are primarily caused by energy-intensive primary production processes, especially mining-related emissions to soil, air, and water (Giljum et al., 2025). Climate change mitigation strategies, like reducing demand and primary production or enhancing secondary production, can thus generate benefits also in other impact categories, such as human toxicity, metal depletion or particulate matter formation (Chapters 2, 3, 5). Likewise, decarbonization measures, particularly the phase-out of coal-based processes and an electrification, yield further co-benefits, e.g., in categories relevant for air and water quality, such as particulate matter, photochemical ozone formation, or in freshwater eutrophication (Chapter 5).

Measures to further reduce impacts and avoid potential environmental trade-offs

On the other hand, our results also suggest that decarbonization strategies may potentially shift burdens to other categories, as it has been found for the key measures of a greener electricity supply and the electrification of steel production processes (Chapter 5). Such potential trade-offs, however, should not be interpreted as arguments against electrification or broader energy system transformation. First, their actual relevance remains uncertain and requires further quantification, as discussed in Chapters 5.4.3. and 6.3.3. Second, these side effects are highly dependent on scenario assumptions, e.g., the electricity mix, and are therefore subject to uncertainty. Rather than discouraging decarbonization efforts, these findings offer valuable guidance for future research directions. More importantly, they identify potential hotspots in future systems and thus reveal options for targeted mitigation measures across supply chains and impact categories. Such measures include, for instance (Chapters 3, 5):

- ionizing radiation, caused by nuclear power generation: improving the treatment of tailings during uranium mining, the processing of spent nuclear fuel, or lowering the shares of nuclear power in the electricity mix;
- land use: adhering to sustainable forestry and biomass supply principles;
- material resource depletion: achieving more sustainable metal cycles to limit primary metal extraction, e.g., prioritizing tellurium, copper, gold, silver, or chromium—although these strongly depend on the metal. Generally, the energy transition is expected to decrease overall mining activity globally (Nijnens et al., 2023);
- human toxicity: improving waste treatment processes, particularly for sulfidic tailings from mining and of furnace slag via landfilling, or implementing waste gas control systems for coke production;

- ozone depletion: although ozone depletion is likely overestimated, our results nevertheless highlight the relevance of global compliance with international treaties, like the Montreal Protocol, to continue the phase-out of ozone-depleting substances, like refrigerant gases.

6.4.3. Relevance beyond the metal sector

With the energy transition and anticipated rising metal demand, metal supply systems and their environmental performance are expected to gain in relevance in the future. As shown in Chapter 3, improvements in metal supply can substantially reduce impacts of low-carbon energy technologies, such as PV panels or Li-ion batteries, in categories like human toxicity, metal depletion, particulate matter, or photochemical oxidant formation. Chapter 4 illustrated the consequences of an electrification of steel production on the energy system in Germany. For instance, electricity demand for future steelmaking in Germany could rise drastically, i.e., 15-fold by 2050. This will require a substantial infrastructure expansion, e.g., a 60% increase in German onshore wind capacity compared to today.

6.4.4. Outlook: The need for holistic approaches

Given the driving role of metal supply impacts to infrastructure and technologies, the background scenarios developed in this work contribute to an improved understanding of future environmental implications not only for metal production but society as a whole. As demonstrated in this thesis, a life cycle perspective and systemic approaches are essential to identify both benefits and trade-offs of future interventions, across impact categories and throughout entire supply chains and related systems.

This work contributes to the efforts of reducing the environmental consequences of metal supply by applying a more systemic and integrated scenario approach and thus supports the methodological advancements of prospective LCA.

However, environmental impact assessments represent only one dimension of the sustainability challenge. Achieving a truly sustainable metal supply and thus society will require more holistic approaches and integrated frameworks that can account for social, economic, and political considerations at both global and local levels.

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