Summary

Metal production is not only highly energy-intensive and a major source of greenhouse gas (GHG) emissions, but also causes substantial environmental impacts in other categories, e.g., related to particulate matter, human toxicity, or land use. Steel supply is the primary contributor to metal-related GHG emissions, whereas copper causes the highest impacts for human health and ecosystem damage, which especially occur during mining.

Historically, these impacts have gradually increased. With a growing population and the need for metal-intensive low-carbon technologies, metal demand is expected to continue growing—posing significant challenges to climate and environmental goals. Next to demand growth, metal supply and its associated environmental impacts are likely to change due to various, partially interrelated developments. For instance, the need for a drastic decarbonization may reduce GHG emissions, e.g., for both steel production, as well as for electricity supply, which is essential to decrease the GHG intensity of future electrified processes. On the other hand, a potential decline in ore grades may intensify mining-related impacts, e.g., for copper or nickel.

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.

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

The primary method employed is life cycle assessment (LCA), which allows to evaluate environmental impacts taking a systems perspective, by representing the entire supply chain and sectoral interdependencies. Specifically, prospective LCA (pLCA) is applied to analyze *future* systems by integrating scenarios. As metal production is closely interrelated with the energy sector, this work addresses the methodological challenge of consistently integrating multi-sectoral scenarios for interlinked sectors into one pLCA model, specifically, a life cycle inventory (LCI) database. Such an *integrated* approach ensures that sectoral interdependencies can be accounted for.

Chapter 2 provides an overview of existing research on the future environmental impacts of metal supply using a systemic literature review. It summarizes estimated impact trends, key drivers as well as methodological approaches applied in prior studies.

The results showed that the future impacts of metals are so far insufficiently addressed by existing research. The 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). Metals crucial for the energy transition, e.g., lithium or neodymium, are rarely addressed, unlike major metals.

The review revealed that specific impacts (per kg of metal) may decrease driven by, e.g., greener electricity, higher recycling shares, or novel technologies. Nevertheless, this decrease is probably insufficient to compensate for rising demand, another key driver. Thus, demand-related impacts are still likely to increase.

The ultimate magnitude of impacts remains unclear due to highly diverse research scopes, scenario assumptions and narratives, which considerably influence results. 15 scenario variables and 229 unique data sources were found.

This qualitative review identified key recommendations, such as the need for further quantitative impact assessments ideally using scenarios with aligned storylines and considering key drivers, like metal demand, an energy transformation and novel production technologies—an approach pursued in Chapters 3–5.

Chapter 3 assesses the effects of potentially declining ore grades alongside developments in metal and electricity supply. A prospective life cycle assessment (pLCA) was conducted for copper, nickel, zinc, and lead—metals for which declining ore grades have been documented. The developed metal supply scenarios cover five key developments: ore grades, primary production locations, energy-efficiency improvements, technology mix for primary production, and shares of primary and secondary production. These were combined with electricity supply scenarios from the integrated assessment model (IAM) IMAGE, into one LCI database to achieve an *integrated* approach, that is, future metal supply chains make use of future electricity and vice versa.

The 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. The effect of declining ore grades can largely be offset by increasing recycling shares and greener electricity supply.

The integrated scenario approach proved essential to evaluate the joint effect of electricity and metal supply changes, as they influence impacts complementarily and in different categories. While a greener electricity especially drives climate impacts, improvements in mining and metal production are key to lowering human toxicity. The analysis also showed that advances in metal supply can reduce the impacts of low-carbon energy technologies, such as human toxicity or metal depletion.

Chapter 4 assesses the CO_2 emission reduction potential of emerging iron and steel production technologies through a case study on Germany, Europe's largest steel producer. We modelled current and emerging steel production routes accounting for energy- and reaction-related CO_2 emissions as well as future German electricity mixes. Three decarbonization pathways were developed to reflect technology diffusion by 2050.

The analysis showed that electrified technologies—hydrogen-based direct reduction (H2-DRI), electrowinning (EW), and scrap-based electric arc furnaces (scrap-EAF)—offer the highest emission reduction potential if power is decarbonized. They clearly outperform carbon capture and storage technologies for coal-based blast furnace and basic oxygen furnaces (BF-BOF-CCS). Although all decarbonization pathways achieve similar *annual* CO_2 reductions by 2050 (72–83% vs. 2020), their *cumulative* emissions differ substantially. The lowest cumulative emissions were realized when existing BF-BOFs were retrofitted with CCS while simultaneously transitioning to electrified technologies. Nevertheless, all decarbonization scenarios considerably exceeded the sectoral carbon budgets for the 1.5°C and the 1.75°C target for the German steel industry by up to fivefold, even under constant production levels.

The analysis revealed the urgency of more drastic emission reduction strategies and thus highlights the need for comprehensive global assessments of the sector's future emissions, that account for transition pathways to electrified and CCS technologies, developments in related sectors, such as energy supply, and future steel demand.

Expanding the approach of the previous chapter, Chapter 5 assessed the environmental implications of future global steel production using prospective LCA. This comprehensive study examined 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. The steel scenarios cover nine steel production routes, including novel technologies, such as carbon capture and storage (CCS), hydrogen-based or electrified processes; efficiency improvements; as well as region-specific recycling shares; production mixes; and steel demand. A key strength of this assessment was its *integrated* approach, i.e., the use and combination of multi-sectoral, internally consistent steel and energy scenarios from one IAM (IMAGE).

This study confirmed that, also from a life cycle perspective, electrified steel production technologies offer the highest GHG reduction potential achieving up to 95% by 2060 compared to current coke-based processes, provided that decarbonized electricity is used. They thereby clearly outperform CCS technologies for coke-based processes.

Yet, even if transitioning to a more electrified steel production as in the most ambitious 1.5°C scenario, achieving net-zero steel production globally remains unlikely, as average global GHG emissions per kilogram of steel decrease by at most 79% by 2060.

Considering future steel demand growth revealed that global steel production is likely to require disproportionately large shares of the global carbon budgets, up to 30% of the global end-of-the-century budget by 2060 even under the most optimistic 1.5°C scenario.

Moreover, the analysis showed that decarbonization measures may shift burdens from climate change to other impact categories, such as ionising radiation or land use. Due to rising steel demand (61% by 2060), impacts of global steel production are likely to increase in most categories—however, the relevance of these increases remains uncertain and needs to be determined at global and local levels. Rising impacts largely depend on upstream and downstream sectors, especially the electricity mix, but also metal mining, or waste treatment processes.

To conclude, the work presented in this thesis found that although future environmental impacts of metal supply are likely to decline on a per-kilogram-basis for most metals, these reductions are unlikely to fully offset the effects of growing demand. As a result, overall impacts are still expected to rise globally for many metals across several impact

categories. While global GHG emissions of steel supply can be decreased substantially through novel production technologies, these reductions are likely insufficient to meet climate targets. Reducing both climate and non-climate impacts of metal supply will hence require a broad, system-wide portfolio of strategies. These strategies should aim at drastically limiting demand, while increasing recycling, accelerating decommissioning of emission-intensive technologies, a faster ramp up of novel technologies and renewable energy capacities, as well as incentivizing targeted process- and impact-category-specific emission mitigation measures across sectors and supply chains. It further identified the following key findings:

- Declining mined ore grades may increase per-kg impacts, but this effect can largely be offset by other improvements, such as greener electricity and higher recycling rates.
- For steel, electrified or hydrogen-based technologies offer the greatest GHG reduction potential if powered by decarbonized electricity. However, even these best-performing steel production technologies miss the target of climate-neutrality, making net-zero production and compliance with carbon budgets by 2060 unlikely even in the most optimistic scenario.
- Decarbonization measures bring co-benefits in key impact categories but may also involve trade-offs. For steel production, trade-offs are largely—though not solely—linked to future electricity supply, highlighting opportunities for further improvements and the need for multi-sectoral assessments.

This thesis contributes to the advancement of the prospective LCA methodology. First, it provided the first comprehensive background scenarios for metal supply (Chapters 3, 5). Second, it created a knowledge base on the state-of-the-art of impact assessment of metal supply, identified methodological shortcomings, and offers recommendations to improve and harmonize research practices (Chapter 2). Finally, it supported the development of tools to consistently integrate multi-sectoral scenarios into one LCI database, and thus facilitates this essential, but previously complex and obstructive step. This *integrated* approach is transferable to other sectors, thus supporting future studies.

As metal supply impacts are expected to gain in relevance, future research is needed to address additional metals, particularly those with currently high impacts or expected strong demand growth. This should include exploring the effect of demand-side solutions—a topic beyond the scope of this thesis, which focused on developments in metal production—as well as identifying additional measures that keep GHG emissions within carbon budgets while minimizing trade-offs. To better prioritize interventions, future research should assess the relevance of each impact category at both global and local levels, e.g., using frameworks like planetary boundaries or regionalized assessments, as well as define and allocate impact thresholds.

While this work contributes to an improved understanding of future environmental implications of metal production, 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 factors, at both global and local levels.