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

Harpprecht, C.I.

Future Environmental Impacts of Metals

Findings from Integrated Scenario Assessment with Prospective LCA

Carina Isabelle Harpprecht

Future Environmental Impacts of Metals

Findings from Integrated Scenario Assessment
with Prospective LCA

Carina Isabelle Harpprecht

Title: Future Environmental Impacts of Metals.
Subtitle: Findings from Integrated Scenario Assessment with Prospective LCA

PhD Thesis at Leiden University, The Netherlands

Cover design: Carina Isabelle Harpprecht

Cover photograph: Carina Isabelle Harpprecht

Layout: Carina Isabelle Harpprecht

Printing: Kuhn Copyshop & Mediacenter

Future Environmental Impacts of Metals

Findings from Integrated Scenario Assessment with Prospective LCA

Proefschrift

ter verkrijging van

de graad van doctor aan de Universiteit Leiden,

op gezag van waarnemend rector magnificus,

volgens besluit van het college voor promoties

te verdedigen op vrijdag 23 januari 2026

klokke 11:30 uur

door

Carina Isabelle Harpprecht

geboren te Esslingen am Neckar, Duitsland

in 1991

Promotores:

Prof. dr. A. Tukker

Dr. B. R. P. Steubing

Co-promotor:

Dr. T. Naegler (German Aerospace Center)

Promotiecommissie:

Prof. dr. M. G. Vijver

Prof. dr. ir. J. B. Guinée

Prof. dr. E. G. M. Kleijn

Dr. N. Thonemann

Prof. dr. S. Pauliuk (Universität Freiburg)

Prof. dr. I. Tietze (Hochschule Pforzheim)

This work was financially supported by the German Aerospace Center (DLR).

To my mother, whose strength, courage, and loving generosity have always inspired and supported me.

Table of Contents

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.

Samenvatting

De productie van metalen is niet alleen zeer energie-intensief en een belangrijke bron van broeikasgasemissies (BKG), maar veroorzaakt ook aanzienlijke milieueffecten in andere impact categorieën, zoals fijn stof, humane toxiciteit en landgebruik. Staalproductie is de grootste veroorzaker van metaalgerelateerde BKG-emissies, terwijl koperproductie de grootste impact heeft op de menselijke gezondheid en de ecosystemen, met name tijdens de winning van ertsen.

Historisch gezien zijn deze milieueffecten geleidelijk toegenomen. Met een groeiende bevolking en de behoefte aan metaalintensieve en koolstofarme technologieën zal de vraag naar metalen naar verwachting blijven stijgen. Dit levert aanzienlijke uitdagingen op voor klimaat- en milieudoelstellingen. Naast de vraaggroei zullen ook de metaalvoorziening en de daaraan verbonden milieueffecten waarschijnlijk veranderen door verschillende, deels samenhangende ontwikkelingen. Zo kan de noodzaak van een ingrijpende decarbonisatie de BKG-emissies verminderen, zowel in de staalproductie als in de elektriciteitsvoorziening, wat essentieel is om de uitstootintensiteit van toekomstige geëlektrificeerde processen te beperken. Anderzijds kan een mogelijke daling van de ertsgraad (het gehalte aan metaal in een erts) de mijnbouw gerelateerde milieueffecten, bijvoorbeeld bij koperproductie en nikkelproductie, verder verergeren.

In het licht van klimaat- en milieudoelstellingen is het van groot belang de drijvende krachten en hotspots van toekomstige effecten van de metaalvoorziening te identificeren, zodat besluitvorming voor mitigatie effectief kan worden ondersteund. Een goed overzicht van de toekomstige milieu-implicaties van metaalproductie ontbreekt echter nog.

Dit proefschrift richt zich op de beoordeling van de toekomstige milieuprofielen van de metaalvoorziening, met bijzondere aandacht voor de effecten van ertsgraden, decarbonisatieroutes in de staalproductie en ontwikkelingen in gerelateerde systemen, in het bijzonder de elektriciteitsvoorziening.

De belangrijkste toegepaste methode is levenscyclusanalyse (LCA), waarmee milieueffecten vanuit een systeemperspectief kunnen worden geëvalueerd. LCA geeft namelijk zowel de volledige productieketens als sectorale afhankelijkheden weer. Meer in het bijzonder wordt 'prospective' (toekomstgerichte) LCA (pLCA) toegepast om toekomstige systemen te analyseren door scenario's te integreren. Omdat metaalproductie nauw verbonden is met de energiesector, gaat dit proefschrift in op de methodologische uitdaging om multisectorale scenario's voor onderling verbonden sectoren consistent te integreren in één pLCA-model, in het bijzonder een Life cycle intentory (LCI)-database. Een dergelijke *geïntegreerde* aanpak maakt het mogelijk rekening te houden met onderlinge sectorale afhankelijkheden.

Hoofdstuk 2 omvat een systematisch literatuurreview van bestaand onderzoek naar de toekomstige milieueffecten van de metaalvoorziening. Hierin worden toekomstige trends qua milieuimpacts, de belangrijkste drijvende krachten en de toegepaste methodologische benaderingen samengevat.

De resultaten tonen aan de bestaande literatuur onvoldoende aandacht schenkt aan de toekomstige milieueffecten van metalen. De literatuurstudie leverde 40 publicaties op, maar deze richtten zich slechts op 15 metalen (koper, ijzer, aluminium, nikkel, zink, lood, kobalt, lithium, goud, mangaan, neodymium, dysprosium, praseodymium, terbium en titanium). Metalen die cruciaal zijn voor de energietransitie, zoals lithium of neodymium, komen zelden aan bod, in tegenstelling tot de bulkmetalen.

Uit deze studie blijkt dat de specifieke impact (per kilogram metaal) kan afnemen door bijvoorbeeld het gebruik van schonere elektriciteit, een groter aandeel recycling of inzet van nieuwe technologieën. Toch is deze afname waarschijnlijk onvoldoende om de stijgende vraag, een andere belangrijke drijvende kracht, te compenseren. In totaal zullen de milieueffecten van metaalgebruik in de toekomst dus waarschijnlijk blijven toenemen.

De uiteindelijke omvang van de milieueffecten blijft onduidelijk vanwege sterk uiteenlopende onderzoeksopzetten, scenario-aannames en verhaallijnen, die de resultaten aanzienlijk beïnvloeden.

Deze kwalitatieve studie leverde belangrijke aanbevelingen op, waaronder de noodzaak van meer kwantitatieve effectbeoordelingen, bij voorkeur met scenario's die onderling afgestemde verhaallijnen gebruiken en rekening houden met cruciale drijvende krachten zoals de vraag naar metalen, een energietransitie en nieuwe productietechnologieën—een aanpak die in hoofdstukken 3–5 wordt gevolgd.

Hoofdstuk 3 onderzoekt de effecten van mogelijk dalende ertsgraden in samenhang met ontwikkelingen in de metaal- en elektriciteitsproductie. Er werd een prospective levenscyclusanalyse uitgevoerd voor koper, nikkel, zink en lood—metalen waarvoor dalende ertsgehaltes zijn gedocumenteerd. De ontwikkelde scenario's voor de productie van deze metalen omvatten vijf belangrijke aspecten: ertsgraden, locaties van primaire productie, verbeteringen in energie-efficiëntie, de technologiemix voor primaire productie, en de verdeling tussen primaire en secundaire productie. Deze werden gecombineerd met scenario's voor toekomstige elektriciteitsproductie uit het 'integrated assessment model' (IAM) IMAGE, in één LCI-database om een *geïntegreerde* aanpak te realiseren, zodat de voor de toekomst gemodelleerde metaalproductieketens gebruik maken van voor de toekomst gemodelleerde elektriciteit en vice versa.

De resultaten tonen aan dat voor de onderzochte metalen de meeste milieueffecten per kilogram geleverd metaal waarschijnlijk zullen afnemen, ondanks een daling van de ertsgraden. Het effect van afnemende ertsgraad kan grotendeels worden gecompenseerd door hogere recyclingpercentages en een schonere elektriciteitsvoorziening.

De *geïntegreerde* scenarioaanpak bleek essentieel om het gezamenlijke effect van veranderingen in elektriciteits- en metaalvoorziening te evalueren. Elektriciteit wordt gebruikt in metaalproductie en omgekeerd, en deze productieprocessen dragen bij aan heel verschillende typen milieu-impacts. Een koolstofarme elektriciteitsvoorziening reduceert vooral klimaateffecten, maar leidt tot een hogere impact ten aanzien van grondstofgebruik en humane toxiciteit. Verbeteringen in de metaalproductie kunnen juist helpen deze twee effecten te verminderen.

Hoofdstuk 4 beoordeelt het potentieel voor CO_2-emissiereductie van innovatieve productietechnieken voor ijzer- en staal. Dit wordt gedaan aan de hand van een casestudy over Duitsland, de grootste staalproducent van Europa. We hebben huidige en alternatieve staalproductieroutes gemodelleerd, waarbij zowel de proces- en energiegerelateerde CO_2-emissies zijn meegenomen, rekening houdend met de toekomstige Duitse elektriciteitsmixen. Drie decarbonisatieroutes werden ontwikkeld om gebruik van opkomende technologieën tegen 2050 te modelleren.

De analyse toont aan dat geëlektrificeerde technologieën—waterstof-gebaseerde directe reductie (H_2-DRI), electrowinning (EW) en elektrische boogovens die staalschroot omsmelten (scrap-EAF)—het grootste reductiepotentieel bieden, mits de elektriciteitsvoorziening is gedecarboniseerd. Zij presteren duidelijk beter dan technologieën voor koolstofafvang en -opslag (CCS) in traditionele hoogovens die cokes inzetten (Blast Furnace-Basic Oxygen Furnace of BF-BOF-CCS). Hoewel alle decarbonisatieroutes vergelijkbare jaarlijkse CO_2-reducties realiseren tegen 2050 (72–83% t.o.v. 2020), verschillen hun cumulatieve emissies aanzienlijk. De laagste cumulatieve emissies zijn te realiseren wanneer bestaande BF-BOF-installaties worden uitgerust met CCS en tegelijkertijd een overgang naar geëlektrificeerde technologieën plaatsvindt. Toch overschrijden alle scenario's het koolstofbudget voor de 1,5°C- en 1,75°C-doelstelling voor de Duitse staalindustrie tot wel een factor vijf, zelfs bij een gelijkblijvend productievolume van staal.

De analyse benadrukt de urgentie van drastischer reductiestrategieën en onderstreept de noodzaak van wereldwijde, uitgebreide analyses van de toekomstige emissies van de sector, waarin rekening wordt gehouden met transitiepaden naar geëlektrificeerde en CCS-technologieën, ontwikkelingen in verwante sectoren zoals de energievoorziening, en de toekomstige vraag naar staal.

Hoofdstuk 5 breidt de aanpak van het voorgaande hoofdstuk uit en beoordeelt de milieueffecten van de toekomstige mondiale staalproductie met behulp van prospective LCA. Deze uitgebreide studie onderzocht een breed scala aan impactcategorieën in verschillende regio's in de wereld, voor drie klimaatmitigatiescenario's: een 3,5°C-baseline, een <2°C-scenario en een 1,5°C-scenario. De productiescenario's voor staal omvatten negen productieroutes, inclusief nieuwe technologieën zoals CCS, waterstofgebaseerde en geëlektrificeerde processen; efficiëntieverbeteringen; fracties gerecycled staal per regio; productiemixen; en de vraag naar staal. Een belangrijke kracht van deze studie was de *geïntegreerde* aanpak, waarbij multisectorale, intern consistente staal- en energiescenario's uit één IAM (IMAGE) werden gecombineerd.

De resultaten bevestigen dat geëlektrificeerde staalproductietechnologieën, ook vanuit een levenscyclusperspectief, het grootste potentieel voor BKG-reductie bieden. Er kunnen reducties worden gehaald tot wel 95% in 2060 ten opzichte van de huidige cokesgebaseerde processen, op voorwaarde dat elektriciteitsproductie gedecarboniseerd is. Ze presteren daarmee duidelijk beter dan CCS-technologieën voor cokesgebaseerde processen.

Toch blijft, zelfs in het meest ambitieuze 1,5°C-scenario met een overgang naar grootschalige elektrificatie, een mondiale klimaatneutrale staalproductie onwaarschijnlijk. De gemiddelde mondiale BKG-emissies per kilogram staal neemt in 2060 maximaal met 79% af. Dit is onvoldoende om de verwachte hogere vraag naar staal te compenseren. De analyse wijst uit dat de mondiale staalproductie naar verwachting een onevenredig groot deel van de wereldwijde koolstofbudgetten zal opeisen: tot 30% van het mondiale budget tegen 2060, zelfs in het meest optimistische 1,5°C-scenario.

Daarnaast toont de analyse dat decarbonisatiemaatregelen milieubelasting kan verschuiven van klimaatverandering naar andere impactcategorieën, zoals ioniserende straling of landgebruik. Door de verwachte toename van de staalvraag (61% tegen 2060) zullen de effecten van de mondiale staalproductie in de meeste categorieën waarschijnlijk stijgen, maar de mate waarin dit relevant is, blijft onzeker en moet zowel op mondiaal als op lokaal niveau worden bepaald. Deze stijgingen hangen grotendeels af van andere sectoren in de productieketen, met name de elektriciteitsmix, maar ook van mijnbouw- en afvalverwerkingsprocessen.

Samenvattend laat dit proefschrift zien dat, hoewel de toekomstige milieueffecten van de metaalvoorziening per kilogram voor de meeste metalen waarschijnlijk zullen afnemen, deze reducties naar verwachting onvoldoende zijn om de effecten van de groeiende vraag volledig te compenseren. Daardoor zullen de totale mondiale effecten voor veel metalen in verschillende impactcategorieën waarschijnlijk blijven toenemen. Hoewel de mondiale broeikasgasemissies van de staalvoorziening aanzienlijk kunnen worden teruggedrongen door nieuwe productietechnologieën, zullen deze reducties waarschijnlijk onvoldoende zijn om de klimaatdoelstellingen te halen. Het terugdringen van zowel klimaat- als niet-klimaateffecten van de metaalvoorziening vereist daarom een brede, systeemwijde portefeuille van strategieën. Deze strategieën moeten onder andere gericht zijn op een drastische beperking van de vraag, een groter aandeel recycling, een versnelde uitfasering van emissie-intensieve technologieën, een snellere opschaling van nieuwe technologieën en hernieuwbare energiegebruik, en het stimuleren van gerichte emissiereductiemaatregelen die zich richten op specifieke processen en impactcategorieën, in alle sectoren en productieketens.

Dit proefschrift leidt kort gezegd tot de volgende kernbevindingen:

- Dalende ertsgraden kunnen de impact per kilogram verhogen, maar dit effect kan grotendeels worden gecompenseerd door andere verbeteringen, zoals schonere elektriciteit en hogere recyclingpercentages.
- Voor staal bieden geëlektrificeerde of waterstofgebaseerde technologieën het grootste reductiepotentieel voor broeikasgasemissies, mits zij gebruik maken van koolstofarme elektriciteit. Zelfs deze best presterende staalproductietechnologieën bereiken echter geen klimaatneutraliteit. Dit betekent dat een 'net zero' doelstelling

voor staalproductie in 2060 niet haalbaar lijkt, en ook dat de staalproductie een onevenredig deel van de resterende koolstofbudgetten tot 2060 nodig heeft, zelfs in de meest optimistische scenarios.

- Decarbonisatiemaatregelen leveren bijkomende voordelen op in belangrijke impactcategorieën, maar leiden ook tot afwenteling op andere impact categorieen zoals grondstofgebruik en humane toxicologie. Voor de staalproductie wordt deze afwenteling grotendeels—maar niet uitsluitend— veroorzaakt door de toekomstige elektriciteitsvoorziening. Dit geeft het belang aan van milieubeoordelingen die diverse sectoren in samenhang analyseren.

Dit proefschrift levert ook een bijdrage aan de verdere ontwikkeling van de prospective LCA-methodologie. Ten eerste biedt het de eerste uitgebreide achtergrondscenario's voor de metaalvoorziening (hoofdstukken 3 en 5). Ten tweede bouwt het een kennisbasis op over de huidige stand van zaken van milieueffectbeoordelingen van de metaalvoorziening, identificeert het methodologische tekortkomingen en doet het aanbevelingen om onderzoekspraktijken te verbeteren en te harmoniseren (hoofdstuk 2). Ten slotte ondersteunt het de ontwikkeling van instrumenten om multisectorale scenario's consistent te integreren in één LCI-database, en vergemakkelijkt het zo een stap die essentieel is, maar tot dusver vaak complex en belemmerend was. Deze *geïntegreerde* aanpak is overdraagbaar naar andere sectoren en vormt zo een fundament voor toekomstig onderzoek.

Omdat de milieueffecten van de metaalvoorziening naar verwachting steeds belangrijker zullen worden, is verder onderzoek nodig naar andere metalen, met name metalen die momenteel al grote milieueffecten veroorzaken of waarvan een sterke toename in vraag wordt verwacht. Dit zou ook onderzoek kunnen omvatten naar het reduceren van de vraag naar zulke metalen - een onderwerp dat buiten de scope van dit proefschrift valt, dat zich richtte op ontwikkelingen in de metaalproductie—alsmede het identificeren van additionele maatregelen die broeikasgasemissies binnen de beschikbare koolstofbudgetten houden en tegelijkertijd afwenteling naar andere impact categorieën minimaliseren. Om interventies beter te kunnen prioriteren, dient toekomstig onderzoek de relevantie van elke impactcategorie zowel op mondiaal als lokaal niveau te beoordelen, bijvoorbeeld via kaders zoals planetaire grenzen of regionale beoordelingen, en drempelwaarden voor effecten te definiëren en toe te wijzen.

Hoewel dit werk bijdraagt aan een beter begrip van de toekomstige milieu-implicaties van metaalproductie, vormen milieueffectbeoordelingen slechts één dimensie van de duurzaamheidsuitdaging. Het bereiken van een werkelijk duurzame metaalvoorziening—en daarmee van een duurzame samenleving—vereist meer holistische benaderingen en geïntegreerde kaders, die tevens rekening houden met sociale, economische en politieke factoren, zowel op mondiaal als lokaal niveau.

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.

References

Arens, M., Worrell, E., Eichhammer, W., Hasanbeigi, A., & Zhang, Q [Qi] (2017). Pathways to a low-carbon iron and steel industry in the medium-term – the case of Germany.

Journal of Cleaner Production, *163*, 84–98. https://doi.org/10.1016/j.jclepro.2015.12.097

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

Arvidsson, R., Svanström, M., Sandén, B. A., Thonemann, N., Steubing, B., & Cucurachi, S. (2024). Terminology for future-oriented life cycle assessment: review and recommendations. *The International Journal of Life Cycle Assessment*, *29*(4), 607–613. https://doi.org/10.1007/s11367-023-02265-8

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

Baumstark, L., Bauer, N., Benke, F., Bertram, C., Bi, S., Gong, C. C., Dietrich, J. P., Dirnaichner, A., Giannousakis, A., Hilaire, J., Klein, D., Koch, J., Leimbach, M., Levesque, A., Madeddu, S., Malik, A., Merfort, A., Merfort, L., Odenweller, A., . . . Luderer, G. (2021). REMIND2.1: Transformation and innovation dynamics of the energy-economic system within climate and sustainability limits. *Geoscientific Model Development.* Advance online publication. https://doi.org/10.5194/gmd-14-6571-2021

Bhaskar, A., Assadi, M., & Nikpey Somehsaraei, H. (2020). Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen. *Energies*, *13*(3). https://doi.org/10.3390/en13030758

Bisinella, V., Christensen, T. H., & Astrup, T. F. (2021). Future scenarios and life cycle assessment: systematic review and recommendations. *The International Journal of Life Cycle Assessment.* Advance online publication. https://doi.org/10.1007/s11367-021-01954-6

Bleischwitz, R., Hoff, H., Spataru, C., van der Voet, E., & van Deveer, S. D. (2017). *Routledge Handbook of the Resource Nexus*. Routledge.

Chisalita, D.-A., Petrescu, L., Cobden, P., van Dijk, H. A. J., Cormos, A.-M., & Cormos, C.-C. (2019). Assessing the environmental impact of an integrated steel mill with post-combustion CO2 capture and storage using the LCA methodology. *Journal of Cleaner Production*, *211*, 1015–1025. https://doi.org/10.1016/j.jclepro.2018.11.256

Cox, B., Mutel, C. L., Bauer, C., Mendoza Beltran, A., & van Vuuren, D. P. (2018). Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles. *Environ Sci Technol*, *52*(8), 4989–4995. https://doi.org/10.1021/acs.est.8b00261

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

Fischedick, M., Marzinkowski, J., Winzer, P., & Weigel, M. (2014). Techno-economic evaluation of innovative steel production technologies. *Journal of Cleaner Production*, *84*, 563–580. https://doi.org/10.1016/j.jclepro.2014.05.063

Fukushima, Y., & Hirao, M. (2002). A structured framework and language for scenario-based Life Cycle assessment. *The International Journal of Life Cycle Assessment*, *6*.

Gibon, T., Wood, R., Arvesen, A., Bergesen, J. D., Suh, S [Sangwon], & Hertwich, E. G. (2015). A Methodology for Integrated, Multiregional Life Cycle Assessment Scenarios under Large-Scale Technological Change. *Environmental Science & Technology*, *49*(18), 11218–11226. https://doi.org/10.1021/acs.est.5b01558

Graedel, T. E., & van der Voet, E. (2010). *Linkages of Sustainability Edited by*. Cambridge, MA: MIT Press.

Harpprecht, C., Naegler, T., Steubing, B., Tukker, A., & Simon, S. (2022). Decarbonization scenarios for the iron and steel industry in context of a sectoral carbon budget: Germany as a case study. *Journal of Cleaner Production*, *380*, 134846. https://doi.org/10.1016/j.jclepro.2022.134846

Hertwich, E. G., Gibon, T., Bouman, E. A., Arvesen, A., Suh, S [S.], Heath, G. A., Bergesen, J. D., Ramirez, A., Vega, M. I., & Shi, L. (2015). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proc Natl Acad Sci U S a*, *112*(20), 6277–6282. https://doi.org/10.1073/pnas.1312753111

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

IEA. (2019). *2019 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector. Global Alliance for Buildings and Construction, International Energy Agency and the United Nations Environment Programme.*

IRP. (2019). *Global Resources Outlook 2019: Natural Resources for the Future We Want*. A Report of the International Resource Panel. United Nations Environment Programme. United Nations Environment Programme. https://www.un-ilibrary.org/content/books/9789280737417 https://doi.org/10.18356/689a1a17-en

IRP. (2020). *Mineral Resource Governance in the 21st Century: Gearing Extractive Industries Towards Sustainable Development.* A Report by the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya. https://www.un-ilibrary.org/content/books/9789280737790 https://doi.org/10.18356/d4ca45f2-en

ISO (2006). *DIN EN ISO 14040:* Environmental management – Life cycle assessment – Principles and framework. DIN Deutsches Institut für Normung e.V.

Khoo, J. Z., Haque, N., Woodbridge, G., McDonald, R., & Bhattacharya, S. (2017). A life cycle assessment of a new laterite processing technology. *Journal of Cleaner Production*, *142*, 1765–1777. https://doi.org/10.1016/j.jclepro.2016.11.111

Koroma, M. S., Brown, N., Cardellini, G., & Messagie, M. (2020). Prospective Environmental Impacts of Passenger Cars under Different Energy and Steel Production Scenarios. *Energies*, *13*(23). https://doi.org/10.3390/en13236236

Kuipers, K. J., van Oers, L. F., Verboon, M., & van der Voet, E. (2018). Assessing environmental implications associated with global copper demand and supply scenarios from 2010 to 2050. *Global Environmental Change*, *49*(February), 106–115. https://doi.org/10.1016/j.gloenvcha.2018.02.008

Le Blanc, D. (2015). Towards Integration at Last? The Sustainable Development Goals as a Network of Targets. *Sustainable Development*, *23*(3), 176–187. https://doi.org/10.1002/sd.1582

Lechtenböhmer, S., Nilsson, L. J., Åhman, M., & Schneider, C. (2016). Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand. *Energy*, *115*, 1623–1631. https://doi.org/10.1016/j.energy.2016.07.110

Lei, T., Wang, D., Yu, X., Ma, S., Zhao, W., Cui, C., Meng, J., Tao, S., & Guan, D. (2023). Global iron and steel plant CO2 emissions and carbon-neutrality pathways. *Nature*, *622*(7983), 514–520. https://doi.org/10.1038/s41586-023-06486-7

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

Li, F., Chu, M., Tang, J., Liu, Z., Guo, J., Yan, R., & Liu, P. (2022). Thermodynamic performance analysis and environmental impact assessment of an integrated system for hydrogen generation and steelmaking. *Energy*, *241*, 122922. https://doi.org/10.1016/j.energy.2021.122922

Mendoza Beltran, A., Cox, B., Mutel, C., Vuuren, D. P., Font Vivanco, D., Deetman, S., Edelenbosch, O. Y., Guinée, J., & Tukker, A. (2018). When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment. *Journal of Industrial Ecology*, *24*(1), 64–79. https://doi.org/10.1111/jiec.12825

Mutel, C. L., & Vandepaer, L. (2017). *Wurst examples repository.*

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

Nuss, P., & Eckelman, M. J. (2014). Life cycle assessment of metals: a scientific synthesis. *PloS One*, *9*(7), e101298.

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

Pauliuk, S., Arvesen, A., Stadler, K., & Hertwich, E. G. (2017). Industrial ecology in integrated assessment models. *Nature Climate Change*, *7*(1), 13–20. https://doi.org/10.1038/nclimate3148

Reinhard, J., Wernet, G., Zah, R., Heijungs, R., & Hilty, L. M. (2019). Contribution-based prioritization of LCI database improvements: the most important unit processes in ecoinvent. *The International Journal of Life Cycle Assessment*, *24*(10), 1778–1792. https://doi.org/10.1007/s11367-019-01602-0

Rosner, F., Papadias, D., Brooks, K., Yoro, K., Ahluwalia, R., Autrey, T., & Breunig, H. (2023). Green steel: design and cost analysis of hydrogen-based direct iron reduction. *Energy & Environmental Science*, *16*(10), 4121–4134. https://doi.org/10.1039/D3EE01077E

Ryan, N. A., Miller, S. A., Skerlos, S. J., & Cooper, D. R. (2020). Reducing CO2 Emissions from U.S. Steel Consumption by 70% by 2050. *Environ Sci Technol*, *54*(22), 14598–14608. https://doi.org/10.1021/acs.est.0c04321

Ryberg, M. W., Wang, P., Kara, S., & Hauschild, M. Z. (2018). Prospective Assessment of Steel Manufacturing Relative to Planetary Boundaries: Calling for Life Cycle Solution. *Procedia CIRP*, *69*, 451–456. https://doi.org/10.1016/j.procir.2017.11.021

Sacchi, R., Terlouw, T., Dirnauchner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., & Luderer, G. (2021). PRospective EnvironMental Impact asSEment (premise): a streamlined approach to producing databases for prospective Life Cycle Assessment using Integrated Assessment Models. *Renewable and Sustainable Energy Reviews.* Advance online publication. https://doi.org/10.1016/j.rser.2022.112311

Schenker, V., Kulionis, V., Oberschelp, C., & Pfister, S. (2022). Metals for low-carbon technologies: Environmental impacts and relation to planetary boundaries. *Journal of Cleaner Production*, *372*, 133620. https://doi.org/10.1016/j.jclepro.2022.133620

Schlichenmaier, S., & Naegler, T. (2022). May material bottlenecks hamper the global energy transition towards the 1.5 °C target? *Energy Reports*, *8*, 14875–14887. https://doi.org/10.1016/j.egyr.2022.11.025

Speizer, S., Durga, S., Blahut, N., Charles, M., Lehne, J., Edmonds, J., & Yu, S. (2023). Rapid implementation of mitigation measures can facilitate decarbonization of the global steel sector in 1.5°C-consistent pathways. *One Earth*, *6*(11), 1494–1509. https://doi.org/10.1016/j.oneear.2023.10.016

Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, M., & Prins, A. (2014). *Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model description and policy applications.*

Steubing, B., Mendoza Beltran, A., & Sacchi, R. (2023). Conditions for the broad application of prospective life cycle inventory databases. *The International Journal of Life Cycle Assessment*, *28*(9), 1092–1103. https://doi.org/10.1007/s11367-023-02192-8

Thonemann, N., Schulte, A., & Maga, D. (2020). How to Conduct Prospective Life Cycle Assessment for Emerging Technologies? A Systematic Review and Methodological Guidance. *Sustainability*, *12*(3), 1192. https://doi.org/10.3390/su12031192

Toktarova, A., Karlsson, I., Rootzén, J., Göransson, L., Odenberger, M., & Johnsson, F. (2020). Pathways for Low-Carbon Transition of the Steel Industry—A Swedish Case Study. *Energies*, *13*(15). https://doi.org/10.3390/en13153840

UNEP. (2013). *Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles, A Report of the Working Group on the Global Metal Flows to the International Resource Panel* (ISBN: 9789280732665). https://doi.org/10.1227/01.NEU.0000108643.94730.21

van der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G. J., & Tukker, A. (2020). A critical view on the current application of LCA for new technologies and recommendations for improved practice. *Journal of Cleaner Production*, *259*, 120904. https://doi.org/10.1016/j.jclepro.2020.120904

van der Voet, E., van Oers, L., Verboon, M., & Kuipers, K. (2019). Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals. *Journal of Industrial Ecology*, *23*(1), 141–155. https://doi.org/10.1111/jiec.12722

van Ruijven, B. J., van Vuuren, D. P., Boskaljon, W., Neelis, M. L., Saygin, D., & Patel, M. K. (2016). Long-term model-based projections of energy use and CO2 emissions from the global steel and cement industries. *Resources, Conservation and Recycling*, *112*, 15–36. https://doi.org/10.1016/j.resconrec.2016.04.016

van Sluisveld, M. A., Boer, H. S. de, Daioglou, V., Hof, A. F., & van Vuuren, D. P. (2021). A race to zero - Assessing the position of heavy industry in a global net-zero CO2 emissions context. *Energy and Climate Change*, *2*, 100051. https://doi.org/10.1016/j.egycc.2021.100051

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., & Rose, S. K. (2011). The representative concentration pathways: an overview. *Climatic Change*, *109*(1-2), 5–31. https://doi.org/10.1007/s10584-011-0148-z

Wang, P., Ryberg, M., Yang, Y., Feng, K., Kara, S., Hauschild, M., & Chen, W. Q. (2021). Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. *Nat Commun*, *12*(1), 2066. https://doi.org/10.1038/s41467-021-22245-6

Wang, Y [Yaxin], Liu, J., Tang, X., Wang, Y [Yu], An, H., & Yi, H. (2023). Decarbonization pathways of China's iron and steel industry toward carbon neutrality. *Resources, Conservation and Recycling*, *194*, 106994. https://doi.org/10.1016/j.resconrec.2023.106994

Watari, T., Cabrera Serrenho, A., Gast, L., Cullen, J., & Allwood, J. (2023). Feasible supply of steel and cement within a carbon budget is likely to fall short of expected global demand. *Nature Communications*, *14*(1), 7895. https://doi.org/10.1038/s41467-023-43684-3

Watari, T., Nansai, K., & Nakajima, K. (2020). Review of critical metal dynamics to 2050 for 48 elements. *Resources, Conservation and Recycling*, *155*, 104669. https://doi.org/10.1016/j.resconrec.2019.104669

Watari, T., Nansai, K., & Nakajima, K. (2021). Major metals demand, supply, and environmental impacts to 2100: A critical review. *Resources, Conservation and Recycling*, *164*, 105107. https://doi.org/10.1016/j.resconrec.2020.105107

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

Xu, R., Tong, D., Davis, S. J., Qin, X., Cheng, J., Shi, Q., Liu, Y., Chen, C., Yan, L., Yan, X., Wang, H., Zheng, D., He, K., & Zhang, Q [Qiang] (2023). Plant-by-plant decarbonization strategies for the global steel industry. *Nature Climate Change*, *13*(10), 1067–1074. https://doi.org/10.1038/s41558-023-01808-z

Yokoi, R., Watari, T., & Motoshita, M. (2022). Future greenhouse gas emissions from metal production: gaps and opportunities towards climate goals. *Energy & Environmental Science*, *15*(1), 146–157. https://doi.org/10.1039/d1ee02165f

Zhang, X., Jiao, K., Zhang, J., & Guo, Z. (2021). A review on low carbon emissions projects of steel industry in the World. *Journal of Cleaner Production.* Advance online publication. https://doi.org/10.1016/j.jclepro.2021.127259

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

This chapter has been published as:

Harpprecht, C., Miranda Xicotencatl, B., van Nielen, S., van der Meide, M., Li, C., Li, Z., Tukker, A., & Steubing, B. (2024). Future environmental impacts of metals: a systematic review of impact trends, modelling approaches, and challenges. *Resources, Conservation and Recycling*, *205*, 107572. https://doi.org/10.1016/j.resconrec.2024.107572

The supplementary information (SI) is available at:

https://ars.els-cdn.com/content/image/1-s2.0-S0921344924001678-mmc1.pdf

Abstract

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

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

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

2.1. Introduction

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

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

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

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

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

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

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

The differences in research scopes concerns, for example:

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

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

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

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

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

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

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

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

---

[3] Ambrose and Kendall (2020); Langkau and Erdmann (2021); van der Meide et al. (2022); Wang et al. (2021); Watari et al. (2022).

[4] Ciacci et al. (2020); Koroma et al. (2020).

[5] Dong et al. (2020); Li et al. (2021).

[6] Farjana et al. (2019).

[7] Memary et al. (2012); Tan and Khoo (2005).

[8] van der Voet et al. (2019); Harpprecht et al. (2021); van der Meide et al. (2022).

[9] Kumar Katta et al. (2020); Song et al. (2017).

[10] Chisalita et al. (2019); Li et al. (2022).

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

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

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

2.2. Methods

2.2.1. Literature search

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

Search methods

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

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

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

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

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

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

Screening

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

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

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

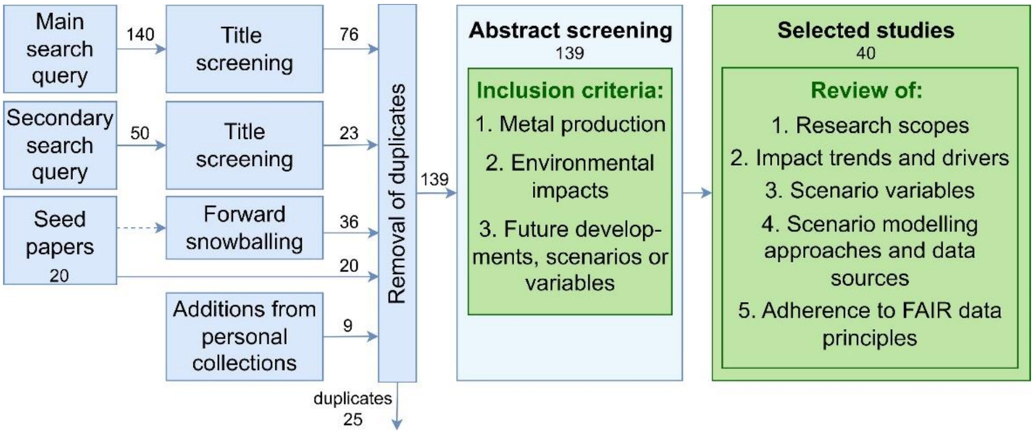


Fig. 1: Overview of the applied approach for the literature search. The abstract screening is documented in Harpprecht et al. (2023), Tables B.1, B2. FAIR: findable, accessible, interoperable and reusable.

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

2.2.2. Assessment of research scopes

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

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

Definitions are provided in Table 1.

2.2.3. Assessment of impact trends

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

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

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

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

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

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

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

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

Table 1: Definition of terms used in this study.

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

2.2.4. Evaluation of scenario variables

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

2.2.5. Evaluation of scenario modelling approaches and data sources

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

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

2.2.6. Adherence to FAIR data principles

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

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

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

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

2.3. Results

2.3.1. Research scopes of reviewed papers

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

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

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

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

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

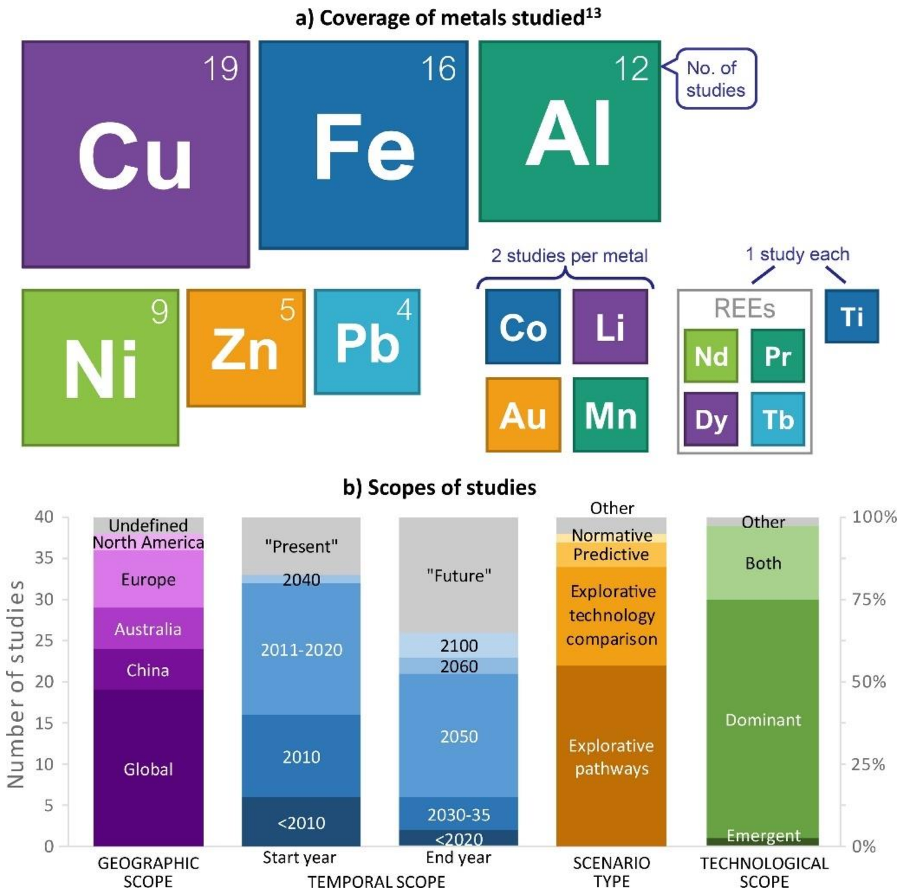


Fig. 2: Overview of metals and scopes covered in the reviewed studies. a) Coverage of metals studied and number of studies per metal[13]; b) Distribution of scope choices and scenario types for reviewed studies. The temporal scope refers to the first and last year analysed. Definitions of terms are provided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

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

2.3.2. Trends and drivers of future impacts of metal supply

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

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

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

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

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

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

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

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

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

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

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

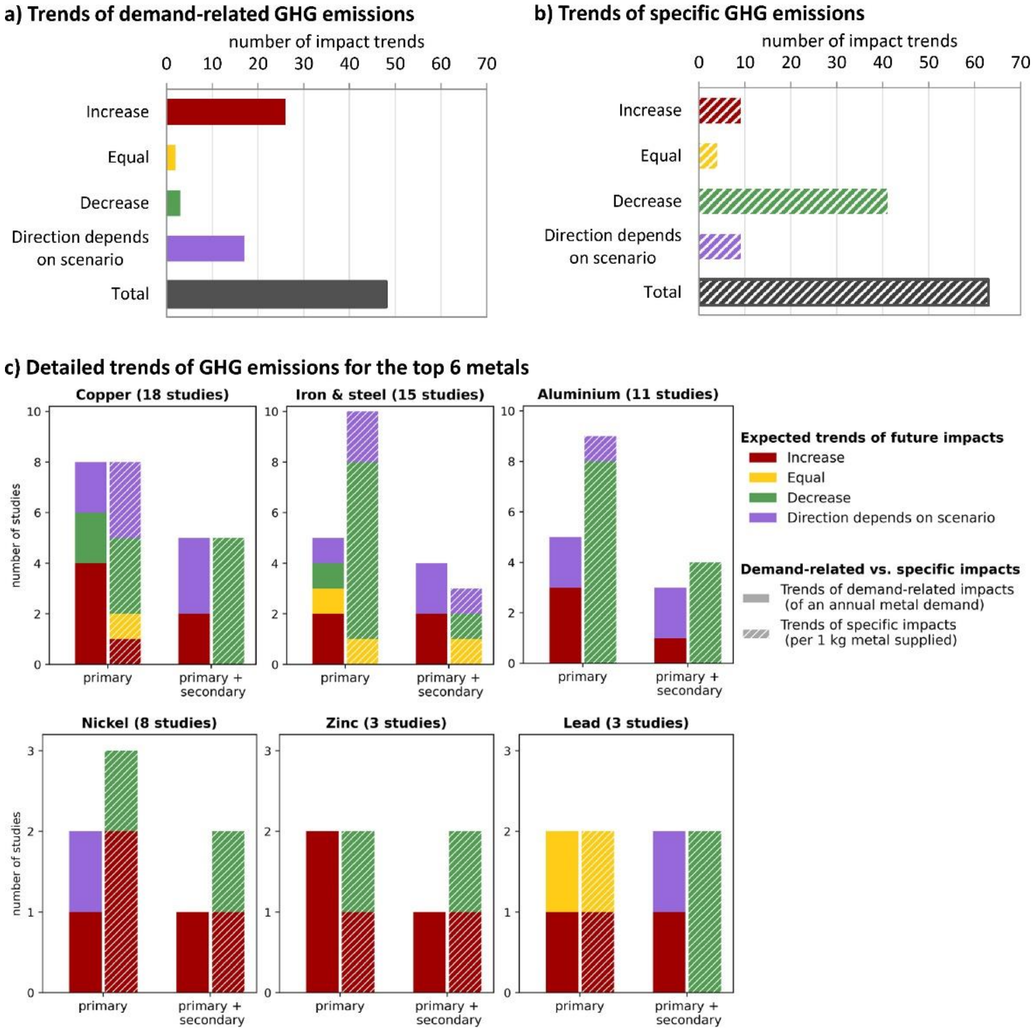


Fig. 3: Trends of future GHG emissions according to the reviewed studies. a) and b) aggregate the data for all metals. C) Results only for the six metals studied the most (n>=3). Demand-related impacts (solid bar) represent trends of GHGs of a future annual demand of a metal. Specific impacts (hatched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

Copper

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

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

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

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

Iron and steel

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

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

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

Aluminium

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

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

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

Nickel

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

Zinc

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

Lead

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

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

Others

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

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

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

2.3.3. Scenario variables

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

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

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

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

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

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

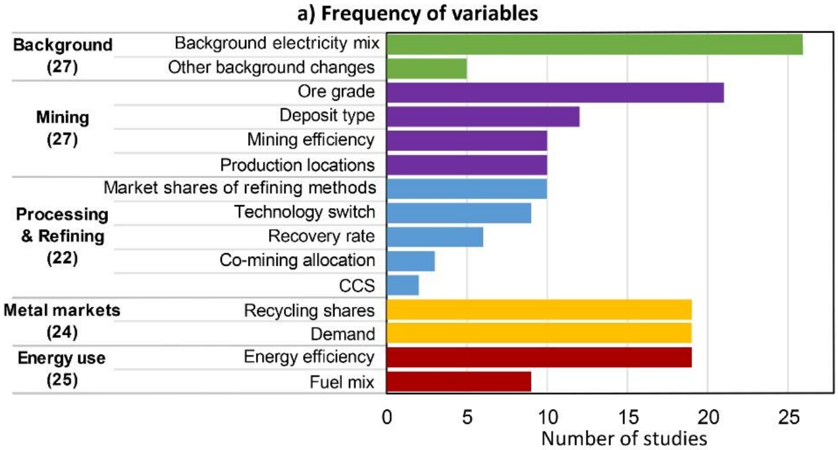
Variable category	Scenario variables	Description
Background system	Background electricity mix	Scenarios for electricity supply in the background system of the LCA model
	Other background changes	Changes in upstream production, e.g., of chemicals
Mining	Ore grade	Metal concentration in the mined ore
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

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

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

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

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



b) Scenario variables studied per metal

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

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

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

2.3.4. Scenario modelling approaches and data sources

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

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

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

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

a) Most common modelling approaches

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

b) Most common data sources

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

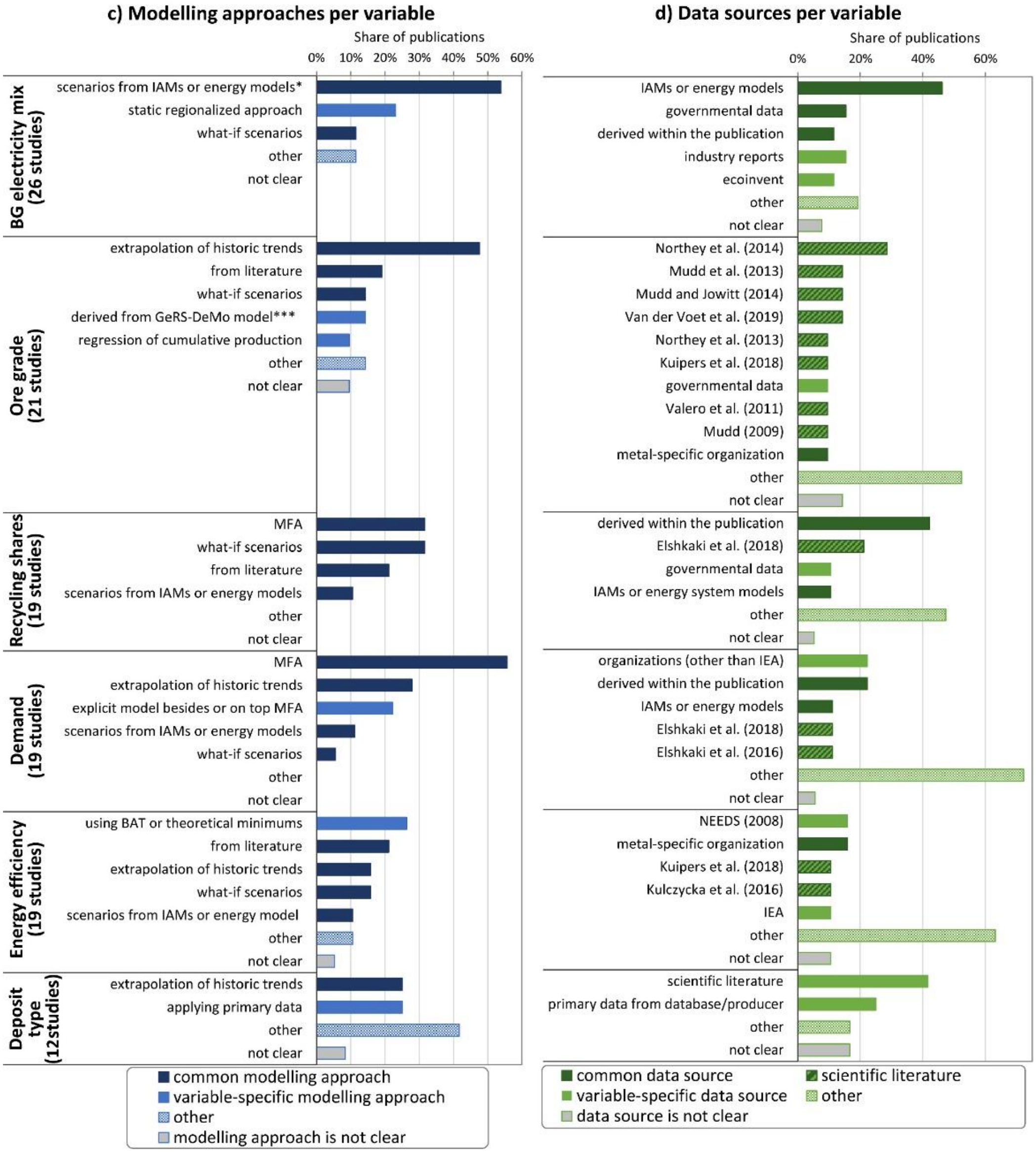


*Fig. 5: Identified categories for scenario modelling approaches and data sources for variables which appear in more than 10 studies. The categories are not mutually exclusive. "not clear" indicates that the required information cannot be derived from the original publication. If no bar is shown, the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

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

2.3.5. Adherence to FAIR data principles

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

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

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

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

2.4. Discussion

2.4.1. Key findings

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

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

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

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

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

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

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

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

2.4.2. Identified challenges and recommendations

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

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

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

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

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

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

2.4.3. Comparison with previous reviews

Our results largely align with findings of previous literature reviews.

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

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

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

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

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

2.4.4. Limitations and future research

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

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

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

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

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

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

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

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

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

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

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

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

2.5. Conclusions

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

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

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

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

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

References

Alexander, C., Johto, H., Lindgren, M., Pesonen, L., Roine, A., 2021. Comparison of environmental performance of modern copper smelting technologies. Cleaner Environmental Systems 3, 100052. https://doi.org/10.1016/j.cesys.2021.100052

Ali, S.H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enriquez, M.A., Kinnaird, J., Littleboy, A. and Meinert, L.D., 2017. Mineral supply for sustainable development requires resource governance. *Nature*, *543*, 367-372. https://doi.org/10.1038/nature21359

Ambrose, H., Kendall, A., 2020. Understanding the future of lithium: Part 2, temporally and spatially resolved life-cycle assessment modeling. Journal of Industrial Ecology 24, 90–100. https://doi.org/10.1111/jiec.12942

Bailey, G., Orefice, M., Sprecher, B., Önal, M.A.R., Herraiz, E., Dewulf, W., Van Acker, K., 2021. Life cycle inventory of samarium-cobalt permanent magnets, compared to neodymium-iron-boron as used in electric vehicles. Journal of Cleaner Production 286, 125294. https://doi.org/10.1016/j.jclepro.2020.125294

Baumstark, L., Bauer, N., Benke, F., Bertram, C., Bi, S., Gong, C.C., Dietrich, J.P., Dirnaichner, A., Giannousakis, A., Hilaire, J., Klein, D., Koch, J., Leimbach, M., Levesque, A., Madeddu, S., Malik, A., Merfort, A., Merfort, L., Odenweller, A., Pehl, M., Pietzcker, R.C., Piontek, F., Rauner, S., Rodrigues, R., Rottoli, M., Schreyer, F., Schultes, A., Soergel, B., Soergel, D., Strefler, J., Ueckerdt, F., Kriegler, E., Luderer, G., 2021. REMIND2.1: transformation and innovation dynamics of the energy-economic system within climate and sustainability limits. Geosci. Model Dev. 14, 6571–6603. https://doi.org/10.5194/gmd-14-6571-2021

Bisinella, V., Christensen, T.H., Astrup, T.F., 2021. Future scenarios and life cycle assessment: systematic review and recommendations. Int J Life Cycle Assess 26, 2143–2170. https://doi.org/10.1007/s11367-021-01954-6

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., Finnveden, G., 2006. Scenario types and techniques: Towards a user’s guide. Futures 38, 723–739. https://doi.org/10.1016/j.futures.2005.12.002

Breyer, C., Khalili, S., Bogdanov, D., Ram, M., Oyewo, A.S., Aghahosseini, A., Gulagi, A., Solomon, A.A., Keiner, D., Lopez, G. and Østergaard, P.A., 2022. On the history and future of 100% renewable energy systems research. *IEEE Access*, *10*, 78176-78218. https://doi.org/10.1109/ACCESS.2022.3193402

Chen, W. Q., & Graedel, T. E., 2012. Anthropogenic cycles of the elements: A critical review. *Environmental science & technology*, *46*(16), 8574-8586. https://doi.org/10.1021/es3010333

Chisalita, D.-A., Petrescu, L., Cobden, P., van Dijk, H.A.J. (Eric), Cormos, A.-M., Cormos, C.-C., 2019. Assessing the environmental impact of an integrated steel mill with post-combustion CO_2 capture and storage using the LCA methodology. Journal of Cleaner Production 211, 1015–1025. https://doi.org/10.1016/j.jclepro.2018.11.256

Ciacci, L., Fishman, T., Elshkaki, A., Graedel, T.E., Vassura, I., Passarini, F., 2020. Exploring future copper demand, recycling and associated greenhouse gas emissions in the EU-28. Global Environmental Change 63, 102093. https://doi.org/10.1016/j.gloenvcha.2020.102093

Cole, V., Boutet, M., 2023. ResearchRabbit (product review). Journal of the Canadian Health Libraries Association / Journal de l'Association des bibliothèques de la santé du Canada 44, 43–47. https://doi.org/10.29173/jchla29699

de Koning, A., Kleijn, R., Huppes, G., Sprecher, B., van Engelen, G., Tukker, A., 2018. Metal supply constraints for a low-carbon economy? Resources, conservation and recycling 129, 202–208. https://doi.org/10.1016/j.resconrec.2017.10.040

Dong, D., van Oers, L., Tukker, A., van der Voet, E., 2020. Assessing the future environmental impacts of copper production in China: Implications of the energy transition. J. Clean Prod. 274, 122825. https://doi.org/10.1016/j.jclepro.2020.122825

Eckelman, M.J., 2010. Facility-level energy and greenhouse gas life-cycle assessment of the global nickel industry. Resources, Conservation and Recycling 54, 256–266. https://doi.org/10.1016/j.resconrec.2009.08.008

Elshkaki, A., 2021. Sustainability of emerging energy and transportation technologies is impacted by the coexistence of minerals in nature. Communications earth & environment 2, 1–13. https://doi.org/10.1038/s43247-021-00262-z

Elshkaki, A., 2020. Long-term analysis of critical materials in future vehicles electrification in China and their national and global implications. Energy (Oxford) 202, 117697-. https://doi.org/10.1016/j.energy.2020.117697

Elshkaki, A., 2019. Material-energy-water-carbon nexus in China's electricity generation system up to 2050. Energy 189, 116355. https://doi.org/10.1016/j.energy.2019.116355

Elshkaki, A., Graedel, T.E., 2015. Solar cell metals and their hosts: A tale of oversupply and undersupply. Applied energy 158, 167–177. https://doi.org/10.1016/j.apenergy.2015.08.066

Elshkaki, A., Graedel, T.E., Ciacci, L. and Reck, B.K., 2016. Copper demand, supply, and associated energy use to 2050. *Global environmental change*, *39*, 305-315. https://doi.org/10.1016/j.gloenvcha.2016.06.006

Elshkaki, A., Graedel, T.E., Ciacci, L., Reck, B.K., 2018. Resource Demand Scenarios for the Major Metals. Environ. Sci. Technol. 52, 2491–2497. https://doi.org/10.1021/acs.est.7b05154

Elshkaki, A., Lei, S., Chen, W.-Q., 2020. Material-energy-water nexus: Modelling the long term implications of aluminium demand and supply on global climate change up to 2050. Environmental research 181, 108964–108964. https://doi.org/10.1016/j.envres.2019.108964

Elshkaki, A., Reck, B.K., Graedel, T.E., 2017. Anthropogenic nickel supply, demand, and associated energy and water use. Resources, Conservation and Recycling 125, 300–307. https://doi.org/10.1016/j.resconrec.2017.07.002

Farjana, S.H., Huda, N., Mahmud, M.A.P., 2019a. Impacts of aluminum production: A cradle to gate investigation using life-cycle assessment. Science of The Total Environment 663, 958–970. https://doi.org/10.1016/j.scitotenv.2019.01.400

Farjana, S.H., Huda, N., Mahmud, M.P. and Saidur, R., 2019b. A review on the impact of mining and mineral processing industries through life cycle assessment. Journal of Cleaner Production, 231, 1200-1217. https://doi.org/10.1016/j.jclepro.2019.05.264

Farjana, S.H., Li, W., 2021. Integrated LCA-MFA Framework for Gold Production from Primary and Secondary Sources. Procedia CIRP, The 28th CIRP Conference on Life Cycle Engineering, March 10 – 12, 2021, Jaipur, India 98, 511–516. https://doi.org/10.1016/j.procir.2021.01.143

Fu, X., Beatty, D.N., Gaustad, G.G., Ceder, G., Roth, R., Kirchain, R.E., Bustamante, M., Babbitt, C., Olivetti, E.A., 2020. Perspectives on Cobalt Supply through 2030 in the Face of Changing Demand. Environmental science & technology 54, 2985–2993. https://doi.org/10.1021/acs.est.9b04975

Ghose, A., 2024. Can LCA be FAIR? Assessing the status quo and opportunities for FAIR data sharing. *The International Journal of Life Cycle Assessment*, 1-12. https://doi.org/10.1007/s11367-024-02280-3

Guohua, Y., Elshkaki, A., Xiao, X., 2021. Dynamic analysis of future nickel demand, supply, and associated materials, energy, water, and carbon emissions in China. Resources policy 74, 102432. https://doi.org/10.1016/j.resourpol.2021.102432

Harpprecht, C., Miranda Xicotencatl, B., van Nielen, S., van der Meide, M., Li, C., Li, Z., Tukker, A., Steubing, B., 2023. Supplementary data for the article: Future environmental impacts of metals: a systematic review of impact trends, modelling approaches, and challenges. [Dataset] v 1.0.1. Zenodo. https://zenodo.org/doi/10.5281/zenodo.10066583

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

Heijlen, W., Franceschi, G., Duhayon, C., Van Nijen, K., 2021. Assessing the adequacy of the global land-based mine development pipeline in the light of future high-demand scenarios: The case of the battery-metals nickel (Ni) and cobalt (Co). Resources policy 73, 102202-. https://doi.org/10.1016/j.resourpol.2021.102202

Henriksson, P.JG., Cucurachi, S., Guinée, J.B., Heijungs, R., Troell, M., Ziegler, F., 2021. A rapid review of meta-analyses and systematic reviews of environmental footprints of food commodities and diets. Global Food Security 28, 100508. https://doi.org/10.1016/j.gfs.2021.100508

Hertwich, E., Heeren, N., Kuczenski, B., Majeau-Bettez, G., Myers, R.J., Pauliuk, S., Stadler, K., Lifset, R., 2018. Nullius in Verba1: Advancing Data Transparency in Industrial Ecology. Journal of Industrial Ecology 22, 6–17. https://doi.org/10.1111/jiec.12738

IEA, 2020. Iron and Steel Technology Roadmap. International Energy Agency, Paris.

IEA, 2017. World Energy Outlook 2017. International Energy Agency, Paris.

IRENA, 2023. Geopolitics of the energy transition: critical materials. Abu Dhabi: IRENA, International Renewable Energy Agency. http://hdl.handle.net/1854/LU-01H7A3C5XFHPCWZH1M0MNDSXAP

IRP, 2019. Global Resources Outlook 2019: Natural Resources for the Future We Want. Oberle, B., Bringezu, S., Hatfield-Dodds, S., Hellweg, S., Schandl, H., Clement, J., and Cabernard, L., Che, N., Chen, D., Droz-Georget , H., Ekins, P., Fischer-Kowalski, M., Flörke, M., Frank, S., Froemelt , A., Geschke, A., Haupt , M., Havlik, P., Hüfner, R., Lenzen, M., Lieber, M., Liu, B., Lu, Y., Lutter, S., Mehr , J., Miatto, A., Newth, D., Oberschelp , C., Obersteiner, M., Pfister, S., Piccoli, E., Schaldach, R., Schüngel, J., Sonderegger, T., Sudheshwar, A., Tanikawa, H., van der Voet, E., Walker, C., West, J., Wang, Z., Zhu, B. A Report of the International Resource Panel. United Nations Environment Programme. Nairobi, Kenya. https://www.resourcepanel.org/reports/global-resources-outlook

IRP, 2020a. Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. International Resource Panel, Nairobi, Kenya. https://doi.org/10.5281/ZENODO.3542680

IRP, 2020b. Mineral Resource Governance in the 21st Century: Gearing extractive industries towards sustainable development. Ayuk, E. T., Pedro, A. M., Ekins, P., Gatune, J., Milligan, B., Oberle B., Christmann, P., Ali, S., Kumar, S. V, Bringezu, S., Acquatella, J., Bernaudat, L., Bodouroglou, C., Brooks, S., Buergi Bonanomi, E., Clement, J., Collins, N., Davis, K., Davy, A., Dawkins, K., Dom, A., Eslamishoar, F., Franks, D., Hamor, T., Jensen, D., Lahiri-Dutt, K., Mancini, L., Nuss, P., Petersen, I., Sanders, A. R. D. A Report by the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya. https://www.resourcepanel.org/reports/mineral-resource-governance-21st-century

ISO, 2006. ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework (Standard). International Organization for Standardization.

Khoo, J.Z., Haque, N., Woodbridge, G., McDonald, R., Bhattacharya, S., 2017. A life cycle assessment of a new laterite processing technology. Journal of Cleaner Production 142, 1765–1777. https://doi.org/10.1016/j.jclepro.2016.11.111

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

Koroma, M.S., Brown, N., Cardellini, G., Messagie, M., 2020. Prospective Environmental Impacts of Passenger Cars under Different Energy and Steel Production Scenarios. Energies 13, 6236. https://doi.org/10.3390/en13236236

Kuipers, K.J.J., van Oers, L.F.C.M., Verboon, M. and van der Voet, E., 2018. Assessing environmental implications associated with global copper demand and supply scenarios from 2010 to 2050. *Global Environmental Change*, *49*, 106-115. https://doi.org/10.1016/j.gloenvcha.2018.02.008

Kulczycka, J., Lelek, Ł., Lewandowska, A., Wirth, H., & Bergesen, J. D., 2016. Environmental Impacts of Energy-Efficient Pyrometallurgical Copper Smelting Technologies: The Consequences of Technological Changes from 2010 to 2050. Journal of Industrial Ecology, 20(2), 304–316. https://doi.org/10.1111/jiec.12369

Kumar Katta, A., Davis, M., Kumar, A., 2020. Assessment of greenhouse gas mitigation options for the iron, gold, and potash mining sectors. Journal of cleaner production 245, 118718-. https://doi.org/10.1016/j.jclepro.2019.118718

Langkau, S., Erdmann, M., 2021. Environmental impacts of the future supply of rare earths for magnet applications. J. Ind. Ecol. 25, 1034–1050. https://doi.org/10.1111/jiec.13090

Laurent, A., Clavreul, J., Bernstad, A., Bakas, I., Niero, M., Gentil, E., Christensen, T.H. and Hauschild, M.Z., 2014. Review of LCA studies of solid waste management systems–Part II: Methodological guidance for a better practice. Waste management, 34(3), 589-606. https://doi.org/10.1016/j.wasman.2013.12.004

Lechtenböhmer, S., Nilsson, L.J., Åhman, M., Schneider, C., 2016. Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand. Energy (Oxford) 115, 1623–1631. https://doi.org/10.1016/j.energy.2016.07.110

Lee, J.C.K., Wen, Z., 2017. Rare Earths from Mines to Metals: Comparing Environmental Impacts from China's Main Production Pathways. Journal of Industrial Ecology 21, 1277–1290. https://doi.org/10.1111/jiec.12491

Li, F., Chu, M., Tang, J., Liu, Z., Guo, J., Yan, R., Liu, P., 2022. Thermodynamic performance analysis and environmental impact assessment of an integrated system for hydrogen generation and steelmaking. Energy 241, 122922. https://doi.org/10.1016/j.energy.2021.122922

Li, Q., Zhang, W., Li, H., He, P., 2017. CO_2 emission trends of China's primary aluminum industry: A scenario analysis using system dynamics model. Energy Policy 105, 225–235. https://doi.org/10.1016/j.enpol.2017.02.046

Li, S., Zhang, T., Niu, L., Yue, Q., 2021. Analysis of the development scenarios and greenhouse gas (GHG) emissions in China's aluminum industry till 2030. Journal of Cleaner Production 290, 125859. https://doi.org/10.1016/j.jclepro.2021.125859

Liang, Y., Kleijn, R., Tukker, A., van der Voet, E., 2022. Material requirements for low-carbon energy technologies: A quantitative review. Renewable and Sustainable Energy Reviews 161. https://doi.org/10.1016/j.rser.2022.112334

Manjong, N.B., Usai, L., Burheim, O.S., Strømman, A.H., 2021. Life Cycle Modelling of Extraction and Processing of Battery Minerals—A Parametric Approach. Batteries 7, 57. https://doi.org/10.3390/batteries7030057

Marx, J., Schreiber, A., Zapp, P., Walachowicz, F., 2018. Comparative Life Cycle Assessment of NdFeB Permanent Magnet Production from Different Rare Earth Deposits. ACS Sustainable Chem. Eng. 6, 5858–5867. https://doi.org/10.1021/acssuschemeng.7b04165

Matthews, D., 2021. Drowning in the literature? These smart software tools can help. Nature 597, 141–142. https://doi.org/10.1038/d41586-021-02346-4

Mayo-Wilson, E., Li, T., Fusco, N., Dickersin, K., Investigators, for the M., 2018. Practical guidance for using multiple data sources in systematic reviews and meta-analyses (with examples from the MUDS study). Research Synthesis Methods 9, 2–12. https://doi.org/10.1002/jrsm.1277

Memary, R., Giurco, D., Mudd, G., Mason, L., 2012. Life cycle assessment: a time-series analysis of copper. Journal of Cleaner Production 33, 97–108. https://doi.org/10.1016/j.jclepro.2012.04.025

Mendoza Beltran, A., Cox, B., Mutel, C., Vuuren, D.P. van, Vivanco, D.F., Deetman, S., Edelenbosch, O.Y., Guinée, J., Tukker, A., 2018. When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment. Journal of Industrial Ecology 0. https://doi.org/10.1111/jiec.12825

Miranda Xicotencatl, B., Kleijn, R., van Nielen, S., Donati, F., Sprecher, B., Tukker, A., 2023. Data implementation matters: Effect of software choice and LCI database evolution on a comparative LCA study of permanent magnets. Journal of industrial ecology 27, 1252–1265. https://doi.org/10.1111/jiec.13410

Mudd, G.M., 2009. The Sustainability of Mining in Australia: Key Production Trends and Their Environmental Implications for the Future. Department of Civil Engineering, Monash University and Mineral Policy Institute, Melbourne. https://users.monash.edu.au/~gmudd/files/SustMining-Aust-Report-2009-Master.pdf

Mudd, G.M., Memary, R., Northey, S.A., Giurco, D., Mohr, S., Mason, L., 2012. Future Greenhouse Gas Emissions from Copper Mining: Assessing Clean Energy Scenarios (No. ISBN 978-1-922173-48-5). Prepared for CSIRO Minerals Down Under Flagship by Monash University and Institute for Sustainable Futures, UTS, Sydney.

Mudd, G.M., Weng, Z., Jowitt, S.M., 2013. A Detailed Assessment of Global Cu Resource Trends and Endowments. Economic Geology 108, 1163–1183. https://doi.org/10.2113/econgeo.108.5.1163

Mudd, G.M., Jowitt, S.M., 2014. A Detailed Assessment of Global Nickel Resource Trends and Endowments. Economic Geology 109, 1813–1841. https://doi.org/10.2113/econgeo.109.7.1813

Nassar, N.T., Graedel, T.E., Harper, E.M., 2015. By-product metals are technologically essential but have problematic supply. Science Advances 1, e1400180. https://doi.org/10.1126/sciadv.1400180

NEEDS, 2008. NEEDS. Deliverable D15.1: LCA of Background Processes. New Energy Externalities Development for Sustainability. Grant agreement ID: 502687. https://cordis.europa.eu/project/id/502687

Nguyen, R.T., Eggert, R.G., Severson, M.H., Anderson, C.G., 2021. Global Electrification of Vehicles and Intertwined Material Supply Chains of Cobalt, Copper and Nickel. Resources, conservation and recycling 167, 105198-. https://doi.org/10.1016/j.resconrec.2020.105198

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

Norgate, T., Jahanshahi, S., 2011. Reducing the greenhouse gas footprint of primary metal production: Where should the focus be? Miner. Eng. 24, 1563–1570. https://doi.org/10.1016/j.mineng.2011.08.007

Norgate, T.E., Jahanshahi, S., Rankin, W.J., 2007. Assessing the environmental impact of metal production processes. Journal of Cleaner Production, From Cleaner Production to Sustainable Production and Consumption in Australia and New Zealand: Achievements, Challenges, and Opportunities 15, 838–848. https://doi.org/10.1016/j.jclepro.2006.06.018

Northey, S., Haque, N., Mudd, G., 2013. Using sustainability reporting to assess the environmental footprint of copper mining. Journal of Cleaner Production, Special Volume: Sustainable consumption and production for Asia: Sustainability through green design and practice 40, 118–128. https://doi.org/10.1016/j.jclepro.2012.09.027

Northey, S., Mohr, S., Mudd, G.M., Weng, Z., Giurco, D., 2014. Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. Resour. Conserv. Recycl. 83, 190–201. https://doi.org/10.1016/j.resconrec.2013.10.005

Northey, S.A., Mudd, G.M., Saarivuori, E., Wessman-Jääskeläinen, H., Haque, N., 2016. Water footprinting and mining: Where are the limitations and opportunities? Journal of cleaner production 135, 1098–1116. https://doi.org/10.1016/j.jclepro.2016.07.024

Nuss, P., Eckelman, M.J., 2014. Life Cycle Assessment of Metals: A Scientific Synthesis. PLOS ONE 9, e101298. https://doi.org/10.1371/journal.pone.0101298

Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McGuinness, L.A., Stewart, L.A., Thomas, J., Tricco, A.C., Welch, V.A., Whiting, P., Moher, D., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Systematic Reviews 10, 89. https://doi.org/10.1186/s13643-021-01626-4

Pauliuk, S., Fishman, T., Heeren, N., Berrill, P., Tu, Q., Wolfram, P., Hertwich, E.G., 2021. Linking service provision to material cycles: A new framework for studying the resource efficiency-climate change (RECC) nexus. J. Ind. Ecol. 25, 274–287. https://doi.org/10.1111/jiec.13023

Pesonen, H.-L., Ekvall, T., Fleischer, G., Huppes, G., Jahn, C., Klos, Z.S., Rebitzer, G., Sonnemann, G.W., Tintinelli, A., Weidema, B.P., Wenzel, H., 2000. Framework for scenario development in LCA. Int. J. LCA 5, 21. https://doi.org/10.1007/BF02978555

Picatoste, A., Justel, D. and Mendoza, J.M.F., 2022. Circularity and life cycle environmental impact assessment of batteries for electric vehicles: Industrial challenges, best practices and research guidelines. Renewable and Sustainable Energy Reviews, 169, 112941. https://doi.org/10.1016/j.rser.2022.112941

Reinhard, J., Wernet, G., Zah, R., Heijungs, R., Hilty, L.M., 2019. Contribution-based prioritization of LCI database improvements: the most important unit processes in ecoinvent. Int J Life Cycle Assess 24, 1778–1792. https://doi.org/10.1007/s11367-019-01602-0

Ren, K., Tang, X. and Höök, M., 2021. Evaluating metal constraints for photovoltaics: Perspectives from China's PV development. Applied Energy, 282, 116148. https://doi.org/10.1016/j.apenergy.2020.116148

Ren, S., Liu, Y., Ren, G., 2021. Uncovering cleaner method for underground metal mining: Enterprise-level assessment for current and future energy consumption and carbon emission from life-cycle perspective. Minerals 11, 1170. https://doi.org/10.3390/min11111170

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

Rinne, M., Elomaa, H., Lundström, M., 2021. Life cycle assessment and process simulation of prospective battery-grade cobalt sulfate production from Co-Au ores in Finland. Int J Life Cycle Assess 26, 2127–2142. https://doi.org/10.1007/s11367-021-01965-3

Ryberg, M.W., Wang, P., Kara, S., Hauschild, M.Z., 2018. Prospective Assessment of Steel Manufacturing Relative to Planetary Boundaries: Calling for Life Cycle Solution. Procedia CIRP, 25th CIRP Life Cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark 69, 451–456. https://doi.org/10.1016/j.procir.2017.11.021

Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., Luderer, G., 2022. PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renewable and Sustainable Energy Reviews 160, 112311. https://doi.org/10.1016/j.rser.2022.112311

Saavedra-Rubio, K., Thonemann, N., Crenna, E., Lemoine, B., Caliandro, P. and Laurent, A., 2022. Stepwise guidance for data collection in the life cycle inventory (LCI) phase:

Building technology-related LCI blocks. Journal of Cleaner Production, 132903. https://doi.org/10.1016/j.jclepro.2022.132903

Schenker, V., Kulionis, V., Oberschelp, C. and Pfister, S., 2022. Metals for low-carbon technologies: Environmental impacts and relation to planetary boundaries. *Journal of Cleaner Production*, 133620. https://doi.org/10.1016/j.jclepro.2022.133620

Schlichenmaier, S., Naegler, T., 2022. May material bottlenecks hamper the global energy transition towards the 1.5 C target? Energy reports 8, 14875–14887. https://doi.org/10.1016/j.egyr.2022.11.025

Schrijvers, D., Hool, A., Blengini, G.A., Chen, W.Q., Dewulf, J., Eggert, R., van Ellen, L., Gauss, R., Goddin, J., Habib, K. and Hagelüken, C., 2020. A review of methods and data to determine raw material criticality. *Resources, conservation and recycling*, *155*, 104617. https://doi.org/10.1016/j.resconrec.2019.104617

Schulze, R., Lartigue-Peyrou, F., Ding, J., Schebek, L., Buchert, M., 2017. Developing a Life Cycle Inventory for Rare Earth Oxides from Ion-Adsorption Deposits: Key Impacts and Further Research Needs. J. Sustain. Metall. 3, 753–771. https://doi.org/10.1007/s40831-017-0139-z

Segura-Salazar, J., Tavares, L., 2018. Sustainability in the Minerals Industry: Seeking a Consensus on Its Meaning. Sustainability (Basel, Switzerland) 10, 1429-. https://doi.org/10.3390/su10051429

Song, X., Pettersen, J.B., Pedersen, K.B., Røberg, S., 2017. Comparative life cycle assessment of tailings management and energy scenarios for a copper ore mine: A case study in Northern Norway. Journal of Cleaner Production 164, 892–904. https://doi.org/10.1016/j.jclepro.2017.07.021

Sonter, L.J., Dade, M.C., Watson, J.E.M., Valenta, R.K., 2020. Renewable energy production will exacerbate mining threats to biodiversity. Nature communications 11, 4174–4174. https://doi.org/10.1038/s41467-020-17928-5

Sprecher, B., Xiao, Y., Walton, A., Speight, J., Harris, R., Kleijn, R., Visser, G., Kramer, G.J., 2014. Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets. Environ. Sci. Technol. 48, 3951–3958. https://doi.org/10.1021/es404596q

Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, M., Prins, A., 2014. Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications. Netherlands Environmental Assessment Agency (PBL), The Hague. https://dspace.library.uu.nl/bitstream/handle/1874/308545/PBL_2014_Integrated_Assessment_of_Global_Environmental_Change_with_IMAGE_30_735.pdf

Steubing, B., de Koning, D., 2021. Making the use of scenarios in LCA easier: the superstructure approach. Int J Life Cycle Assess 26, 2248–2262. https://doi.org/10.1007/s11367-021-01974-2

Steubing, B., Mendoza Beltran, A., Sacchi, R., 2023. Conditions for the broad application of prospective life cycle inventory databases. The international journal of life cycle assessment 28, 1092–1103. https://doi.org/10.1007/s11367-023-02192-8

Suer, J., Traverso, M., Ahrenhold, F., 2021. Carbon footprint of scenarios towards climate-neutral steel according to ISO 14067. Journal of Cleaner Production 318, 128588. https://doi.org/10.1016/j.jclepro.2021.128588

Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y. and Munksgaard, J., 2004. System boundary selection in life-cycle inventories using hybrid approaches. Environmental science & technology, 38(3), 657-664. https://doi.org/10.1021/es0263745

Sverdrup, H.U., Ragnarsdottir, K.V., 2016. A system dynamics model for platinum group metal supply, market price, depletion of extractable amounts, ore grade, recycling and stocks-in-use. Resources, conservation and recycling 114, 130–152. https://doi.org/10.1016/j.resconrec.2016.07.011

Tan, R.B.H., Khoo, H.H., 2005. An LCA study of a primary aluminum supply chain. Journal of Cleaner Production 13, 607–618. https://doi.org/10.1016/j.jclepro.2003.12.022

Thonemann, N., Schulte, A. and Maga, D., 2020. How to conduct prospective life cycle assessment for emerging technologies? A systematic review and methodological guidance. Sustainability, 12(3), 1192. https://doi.org/10.3390/su12031192

Tisserant, A., Pauliuk, S., 2016. Matching global cobalt demand under different scenarios for co-production and mining attractiveness. Journal of Economic Structures 5, 4. https://doi.org/10.1186/s40008-016-0035-x

Troll, V.R. and Arndt, N.T., 2022. European raw materials resilience—turning a blind eye. Earth Science, Systems and Society, 2, 10058. https://doi.org/10.3389/esss.2022.10058

UN, 2015. FCCC/CP/2015/L.9/Rev.1 - Adoption of the Paris Agreement. United Nations, Conference of the Parties, 12 December 2015, Paris. https://documents-dds-ny.un.org/doc/UNDOC/LTD/G15/283/19/PDF/G1528319.pdf

UN, 2019. The future is now: Science for achieving sustainable development: global sustainable development report 2019. United Nations, Dept. of Economic and Social Affairs, & Independent Group of Scientists appointed by the Secretary-General. https://sustainabledevelopment.un.org/content/documents/24797GSDR_report_2019.pdf

UNDP, 2016. White Paper. Mapping Mining to the Sustainable Development Goals: An Atlas. United Nations Development Programme. https://www.undp.org/sites/g/files/zskgke326/files/publications/Mapping_Mining_SDGs_An_Atlas.pdf

UNEP, 2013. Environmental risks and challenges of anthropogenic metals flows and cycles. United Nations Environment Programme, Nairobi.Vahidi, E., Navarro, J., Zhao, F., 2016. An initial life cycle assessment of rare earth oxides production from ion-adsorption clays. Resources, Conservation and Recycling 113, 1–11. https://doi.org/10.1016/j.resconrec.2016.05.006

Valero, Alicia, Valero, Antonio, Domínguez, A., 2011. Trends of exergy costs and ore grade in global mining, in: Proceedings. Presented at the SDIMI 2011. Sustainable Development in the Minerals Industry, Aachen, Germany, pp. 301–316.

van der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G.J., Tukker, A., 2020. A critical view on the current application of LCA for new technologies and recommendations for improved practice. Journal of Cleaner Production 259, 120904. https://doi.org/10.1016/j.jclepro.2020.120904

van der Meide, M., Harpprecht, C., Northey, S., Yang, Y., Steubing, B., 2022. Effects of the energy transition on environmental impacts of cobalt supply: A prospective life cycle assessment study on future supply of cobalt. Journal of Industrial Ecology n/a. https://doi.org/10.1111/jiec.13258

van der Voet, E., van Oers, L., Verboon, M., Kuipers, K., 2019. Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals. Journal of Industrial Ecology 23, 141–155. https://doi.org/10.1111/jiec.12722

van Nielen, S. S., Kleijn, R., Sprecher, B., Miranda Xicotencatl, B., & Tukker, A., 2022. Early-stage assessment of minor metal recyclability. Resources, Conservation and Recycling, 176, 105881. https://doi.org/10.1016/j.resconrec.2021.105881

Wang, P., Ryberg, M., Yang, Y., Feng, K., Kara, S., Hauschild, M., Chen, W.-Q., 2021. Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. Nat Commun 12, 2066. https://doi.org/10.1038/s41467-021-22245-6

Watari, T., McLellan, B.C., Giurco, D., Dominish, E., Yamasue, E., Nansai, K., 2019. Total material requirement for the global energy transition to 2050: A focus on transport and electricity. Resources, conservation and recycling 148, 91–103. https://doi.org/10.1016/j.resconrec.2019.05.015

Watari, T., Nansai, K. and Nakajima, K., 2020. Review of critical metal dynamics to 2050 for 48 elements. *Resources, Conservation and Recycling*, *155*, 104669. https://doi.org/10.1016/j.resconrec.2019.104669

Watari, T., Nansai, K., Nakajima, K., 2021. Major metals demand, supply, and environmental impacts to 2100: A critical review. Resources, Conservation and Recycling 164, 105107. https://doi.org/10.1016/j.resconrec.2020.105107

Watari, T., Northey, S., Giurco, D., Hata, S., Yokoi, R., Nansai, K., Nakajima, K., 2022. Global copper cycles and greenhouse gas emissions in a 1.5 °C world. Resources, Conservation and Recycling 179, 106118. https://doi.org/10.1016/j.resconrec.2021.106118

Wilkinson, M.D., Dumontier, M., Aalbersberg, Ij.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R., Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S., Heringa, J., ’t Hoen, P.A.C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M.A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., Mons, B., 2016. The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data 3, 160018. https://doi.org/10.1038/sdata.2016.18

WSA, 2016. Factsheet: Energy use in the steel industry. World Steel Association.

Xiao, Y., Watson, M., 2019. Guidance on Conducting a Systematic Literature Review. Journal of Planning Education and Research 39, 93–112. https://doi.org/10.1177/0739456X17723971

Yokoi, R., Watari, T., Motoshita, M., 2022. Future greenhouse gas emissions from metal production: gaps and opportunities towards climate goals. Energy Environ. Sci. 15, 146–157. https://doi.org/10.1039/d1ee02165f

Zhong, X., Hu, M., Deetman, S., Steubing, B., Lin, H.X., Hernandez, G.A., Harpprecht, C., Zhang, C., Tukker, A., Behrens, P., 2021. Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060. Nat Commun 12, 6126. https://doi.org/10.1038/s41467-021-26212-z

Zumsteg, J.M., Cooper, J.S., Noon, M.S., 2012. Systematic Review Checklist: A Standardized Technique for Assessing and Reporting Reviews of Life Cycle Assessment Data. Journal of Industrial Ecology 16, S12–S21. https://doi.org/10.1111/j.1530-9290.2012.00476.x

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

This chapter has been published as:

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

The supporting information is available at:

https://doi.org/10.1111/jiec.13181

Abstract

The environmental benefits of low-carbon technologies, such as photovoltaic (PV) modules, have been under debate since their large-scale deployment will require a drastic increase in metal production. This is of concern since higher metal demand may induce ore grade decline, and can thereby further intensify the environmental footprint of metal supply. To account for this interlinkage known as the “energy-resource nexus", energy and metal supply scenarios need to be assessed in conjunction.

We investigate the trends of future impacts of metal supplies and low-carbon technologies, considering both metal and electricity supply scenarios. We develop metal supply scenarios for copper, nickel, zinc and lead, extending previous work. Our scenarios consider developments such as ore grade decline, energy-efficiency improvements and secondary production shares. We also include two future electricity supply scenarios from the IMAGE model using a recently published methodology. Both scenarios are incorporated into the background database of ecoinvent to realize an integrated modelling approach, i.e., future metal supply chains make use of future electricity and vice versa.

We find that impacts of the modelled metal supplies and low-carbon technologies may decrease in the future. Key drivers for impact reductions are the electricity transition, and increasing secondary production shares.

Considering both metal and electricity scenarios has proven valuable since they drive impact reductions in different categories, namely human toxicity (up to -43%) and climate change (up to -63%), respectively. Thus, compensating for lower ore grades and reducing impacts beyond climate change requires both greener electricity and also sustainable metal supply.

3.1. Introduction

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

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

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

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

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

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

Van der Voet et al. (2018) developed detailed supply scenarios for seven major metals (copper, nickel, zinc, lead, iron, aluminum, and manganese) considering various relevant future developments, such as ore grade decline, energy efficiency improvements, or changes in secondary production shares. They model future electricity systems by adapting electricity mixes in the background according to different energy scenarios (IEA, 2012). Thereby, all processes in the back- and foreground which have electricity as inputs receive the adapted future electricity, or the "futurized" electricity. However, their future metal supply chains are not integrated in the background database but modelled in the foreground, "on top" of the background database. This means that all other processes of the background database still make use of the non-future metal supply chains, such as, the future electricity supply sector (see SI section B.1 for a comparison of scenarios in foreground and background systems).

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

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

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

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

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

To achieve this, we build on approaches and scenarios from previous research as follows. We use the work of Mendoza Beltran et al. (2020) to incorporate electricity scenarios from IMAGE. For the metal supply scenarios, we build on and extend the study of van der Voet et al. (2018), which provides comprehensive supply scenarios for seven metals. We choose four metals whose global GHG emissions are among the top ten of all metals (Nuss & Eckelman, 2014) and for which ore grade decline has been documented: copper, nickel, zinc and lead. We further extend the scenarios of van der Voet et al. (2018), adapt them from ecoinvent version 2.2 to version 3.5, and integrate them into the background database. The metal supply scenarios form the main focus of our work. It is important to stress, that our scenarios should not be seen as predictions, but rather as an exploration of possible future developments and their role for future environmental performances of a product system.

3.2. Methods

3.2.1. Approach overview

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

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

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

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

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

3.2.2. Metal supply scenarios

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

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

The supply chains of the other metals are described in the SI (section B.2). For nickel, we model two different types which cover the majority of the nickel market (van der Voet et al. 2018). Those are “nickel” with a purity of 99.5%, and the less pure “ferronickel”, which contains 25% nickel (see SI section B.2.2).

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

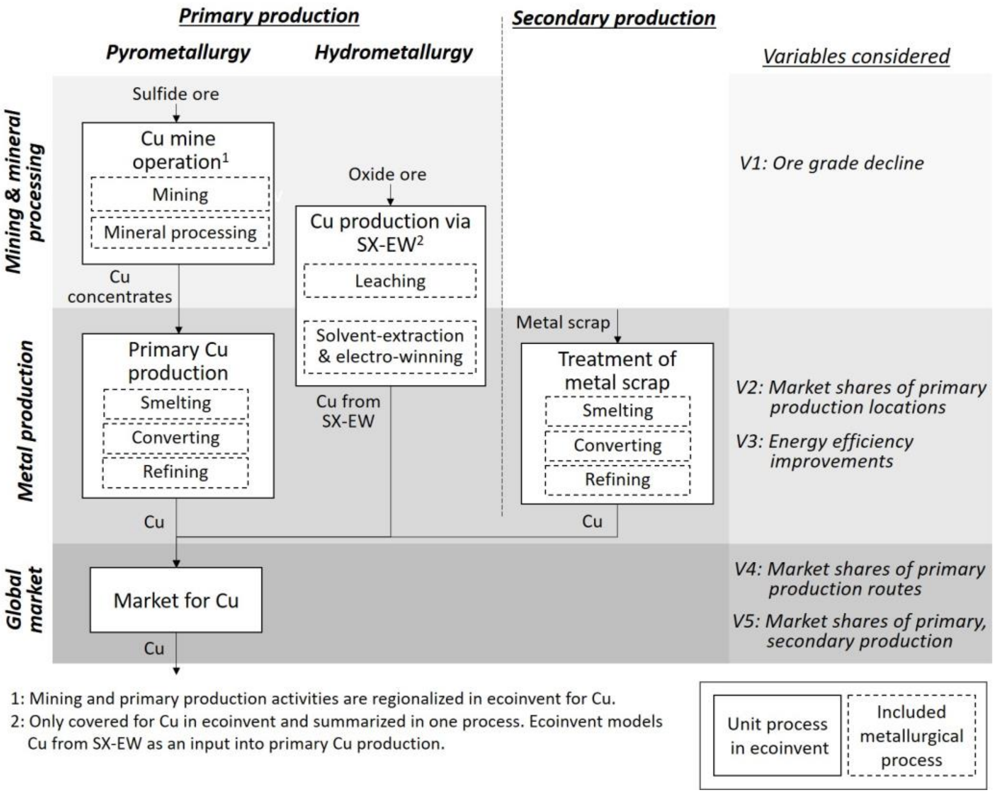


Figure 1: Structure of the copper supply chain in ecoinvent 3.5, the included metallurgical processes, and the modelled variables at each supply stage. Copper mine operation produces a copper concentrate of 30%. Primary copper production refines this concentrate producing refined copper. The supply chains of the other metals are given in the SI (Figures B.3 - B.7). Cu = Cu; SX-EW = SX-EW; V = V.

The data sources used for each variable are shown in Table 1. Differences to the scenarios of van der Voet et al. (2018) mostly lie in the addition of regionalized copper scenarios for variable 1 and 2, and in the adaptation of the variable models to the newer supply chains in ecoinvent v3.5. Each variable is further explained in the following paragraphs with its data being accessible via a repository (Harpprecht et al., 2021). The generated scenarios are then illustrated in the results section in Figure 2.

Table 1: Variables and data sources for the generation of metal supply scenarios. Crucial updates compared to the models of van der Voet et al. (2018) are highlighted in italics. Cu = Cu, FeNi = FeNi; Ni = Ni; Pb = Pb; Zn = Zn.

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

Stage 1: Metal mining

Variable 1: Ore grade decline and energy requirements

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

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

   For nickel, zinc, and lead, $G(t)$ is defined via metal-specific regression models of van der Voet et al. (2018), which are based on historical data (Table 1).

   For copper, future ore grades, $G(t > t_0)$, are defined using data from regionalized models of Northey et al. (2014), specifically their "country-dynamic" scenario. They model copper production amounts and ore grades for 83 regions from 2010 - 2100 with the GeRS-DeMo developed by Mohr (2010). We match their 83 regions to the six pyrometallurgical copper production regions in ecoinvent, and use the production shares of the individual countries as weighing factors to derive an average ore grade per region (see SI section A and Harpprecht et al. (2021)). For $G(t_0)$, historic ore grade data is taken from Mudd & Jowitt (2018).

2. Defining current, $E(t_0)$, and future energy requirements, $E(t > t_0)$, with an ore grade-energy relation, $E(G)$:

   The ore grade-energy relations are taken from van der Voet et al. (2018), who generated them from literature (Table 1) for each metal. With $G(t_0)$, $G(t > t_0)$, and $E(G)$, we define $E(t_0)$ and $E(t > t_0)$ as:

$$E(t_0) = E(G(t_0)),$$

$$E(t > t_0) = E(G(t > t_0)).$$

   Subsequently, we define a factor, $\delta_E(t, t_0)$, which describes how future energy requirements, $E(t > t_0)$, will change relative to current energy requirements, $E(t_0)$ (see SI section B.3.1). As a simplification, which was also used by van der Voet et al. (2018), we assume that this factor, $\delta_E(t)$, can be applied as a proxy to also model the increase and decrease of all other in- and outflows of the mining process (see SI section D.1 for a discussion).

Stage 2: Primary metal production

Variable 2: Market shares of primary production locations

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

We apply the future production shares modelled by Northey et al. (2014) to the production shares per ecoinvent region of copper primary production using the regional match from variable 1 (see SI section B.3.2).

Variable 3: Energy efficiency improvements during smelting and refining

We model a decrease of required electricity and natural gas inputs (-1.77% and -1.5% per year) during smelting and reduction processes within the pyrometallurgical primary production route (SI Figure B.16) with an exponential regression of van der Voet et al. (2018), which was based on projections of Kulczycka et al. (2016).

Stage 3: Market shares of global metal markets

Variable 4: Market shares of primary production routes

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

Variable 5: Market shares of primary and secondary production

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

3.2.3. Electricity supply scenarios

The electricity supply scenarios are taken from Mendoza Beltran et al. (2020), who use IMAGE 3.0 as scenario source (Stehfest et al., 2014) (see SI section B.4). As an IAM, IMAGE models the human system with a focus on energy and land use systems. Mendoza Beltran et al. (2020) use the SSPs of IMAGE (O'Neill et al., 2014). Each pathway consists of a baseline scenario, i.e., how the future develops without additional climate policies, and various mitigation scenarios (Riahi et al., 2017). From those pathways, we select SSP2, the "middle-of-the-road" pathway in which current trends continue without considerable change (Fricko et al., 2017; van Vuuren et al., 2017). From SSP2, we take its baseline and its strongest mitigation scenario, SSP2 and SSP2-2.6. They represent the two extremes within SSP2 (Fricko et al., 2017). SSP2-2.6 describes the strongest mitigation efforts to reach the two-degree target of 450 ppm $CO_2 - eq$..

3.2.4. Incorporating metal and electricity supply scenarios

To analyze the effect of the MS variables and ES scenarios, we adapt the background database, i.e. ecoinvent, with the scenarios described in Table 2. The scenario data is incorporated with *Presamples* (Lesage et al., 2018; Lesage, 2019) and Wurst (Mutel, 2017b) for the MS and ES scenarios, respectively (see SI section B.5).

Table 2: Future scenarios modelled for the prospective LCAs from 2010 to 2050 in time steps of five years. BAU = BAU; ES = ES; MS = MS; PMS = PMS; SMS = SMS; SSP = SSP.

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

3.2.5. Scenario evaluation

Functional units

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

Table 3: Functional units taken from ecoinvent 3.5 for metal supply and metal applications. CH = Switzerland; GLO = GLO; kWp = kWp; Li = Li; Ni = Ni; PV = PV.

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

Impact assessment

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

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

3.3. Results

3.3.1. Development of metal supply variables

Figure 2 illustrates the development of the five variables that feed into the MS scenarios. The modelled decline of mined ore grades into the future (Figure 2.a) results in a corresponding rise in energy requirements (Figure 2.b), with the highest change of +78% being for lead from 2010 to 2050. For copper and nickel energy requirements increase by +24.1% and +11.9% respectively. Variable 3 shows substantial reductions in energy consumption during primary production (smelting and refining) of copper. While ore grade decline, variable 1, will cause an intensification of impacts due to the increasing energy requirements, variables 3 to 5 are expected to have a diminishing effect. The subsequent results show the effect of the states of variables from Figure 2.

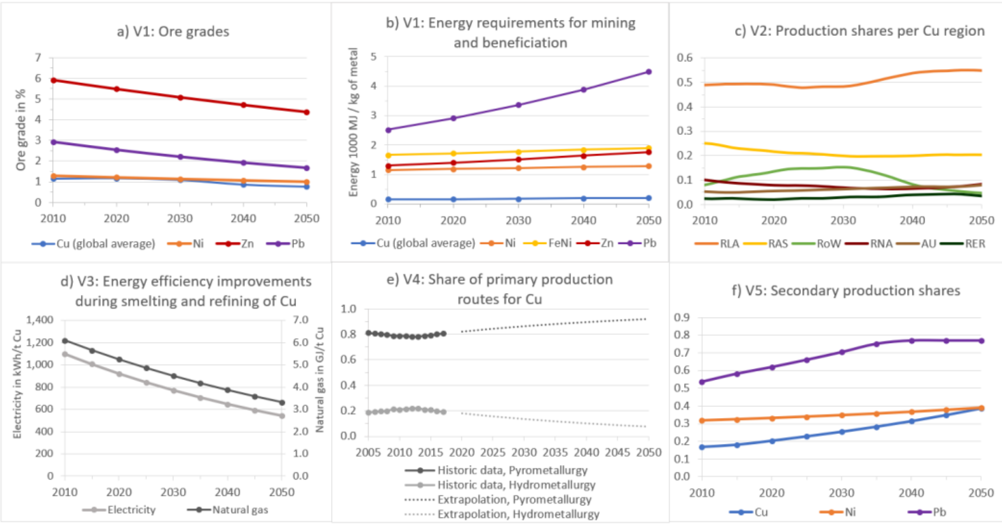


Figure 2: Overview of the applied metal supply scenarios for the five metal supply variables (for a detailed description of each variable, see SI section B.3). The scenario data is accessible via a repository (Harpprecht et al., 2021). For Cu, variable 1, only the global average is shown. The regionalized variables are provided in the SI (Figure B.13). Underlying data used to create this figure can be found in the SI S2. AU = AU; Cu = Cu; GLO = GLO; Ni = Ni; Pb = Pb; RAS = RAS; RER = RER; RLA = RLA; RNA = RNA; RoW = RoW; V = V; Zn = Zn.

3.3.2. Future impacts of metal and electricity supply

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

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

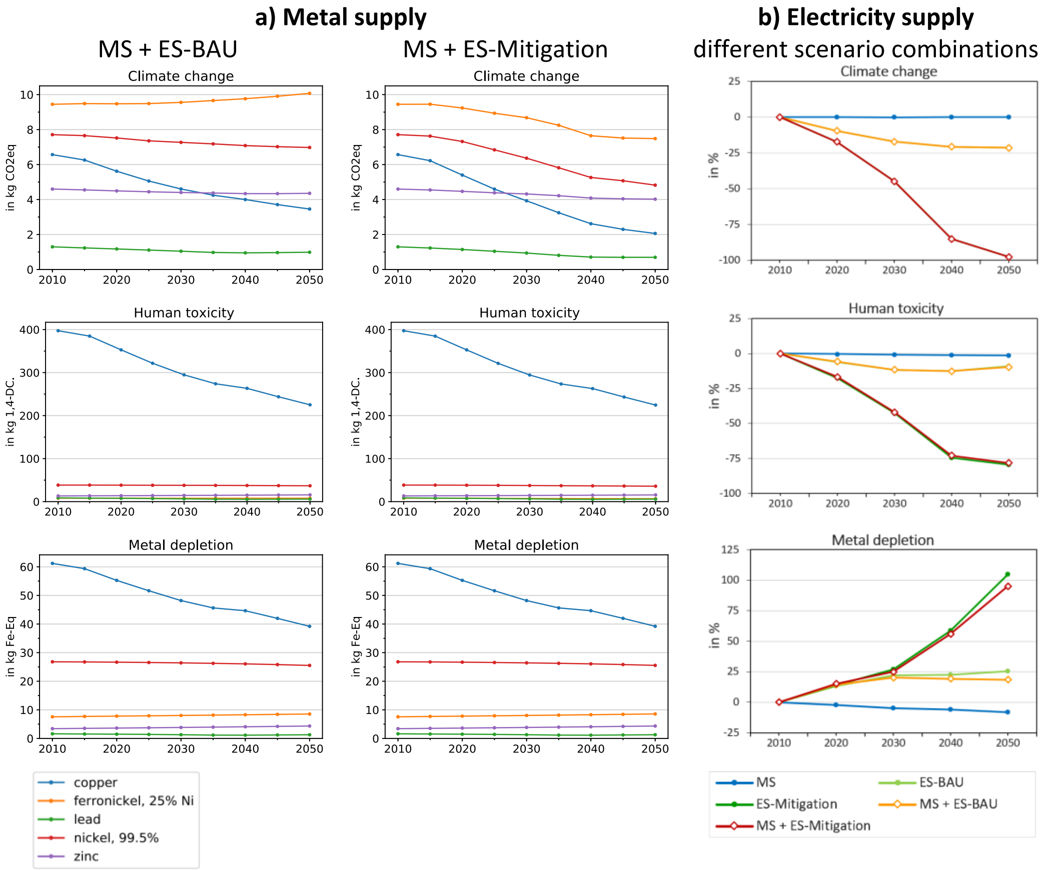


Figure 3: a) Prospective LCA results for the five global metal markets per 1 kg of metal supplied. All metal supply variables are included in combination with electricity scenarios; either the business-as-usual electricity scenario (ES-BAU); or the mitigation electricity scenario (ES-Mitigation). More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

3.3.3. Drivers of future impacts

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

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

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

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

Future metal supply impacts

Incorporating PMS variables causes an impact increase for all metals apart from copper. Lead reveals the strongest increase since it also experiences the strongest decline in ore grade and consequently the highest intensification of energy requirements from 2010 to 2050. Copper's falling PMS impacts can be explained by the fact that its PMS models comprise several variables which have a diminishing effect on impacts, such as variable 3, i.e., reducing energy inputs during smelting and refining, and variable 4, i.e., decreasing hydrometallurgical production shares. The other metals' PMS models only consist of the ore grade decline model which generally increases impacts. Thus, the development of the copper variables 2 to 4 overcompensate for growing impacts associated with falling mined ore grades, which is further investigated later in this article.

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

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

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

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

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

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

Future impacts of low-carbon technologies

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

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

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

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

3.3.4. Drivers of future copper supply impacts

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

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

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

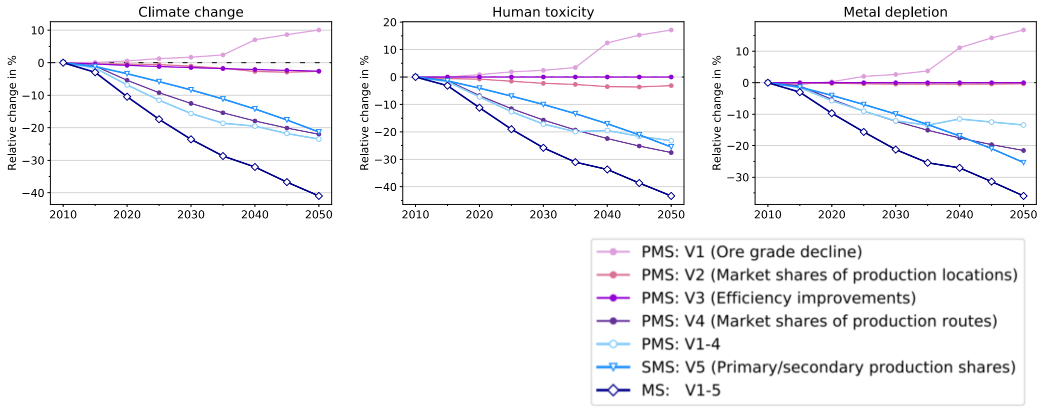


Figure 5: Prospective LCA results for the global market of copper supplying 1 kg of copper: effect of variable 1 to 5. Relative change refers to the impact of the scenario in the given year compared to the impact of 2010. No additional ES scenario is incorporated. For other impact categories see SI Figure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

3.4. Discussion

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

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

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

These findings seem to be consistent with previous studies. A direct comparison with van der Voet et al. (2018) is only partly possible, due to differences, e.g., in modelling approaches, assumed metal supply chains, ecoinvent versions, or choice of ES scenarios and impact categories (see SI section D.2). Our result that declining copper ore grades increase climate change impacts of copper supply by up to 20% is consistent with van der Voet et al. (2018). They also found that a strong electricity scenario can achieve considerable reductions for climate change impacts of metal supply, as well as that it can compensate increasing climate change impacts due to ore grade decline. Moreover, our results are in line with their findings that higher recycling shares can considerably decrease future impacts, and that increasing energy efficiency only has a small effect on primary copper production.

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

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

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

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

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

Another limitation is that we did not include recycling (SMS scenarios, variable 5) for zinc and ferronickel due to (a) a lack of data for ferronickel in the scenarios of Elshkaki et al. (2018); and (b) the fact that zinc's secondary production projections show the lowest increase compared to all other metals within the scenarios of Elshkaki et al. (2018), i.e., less than 5% from 8.1% in 2010 until 2050 (see SI, Figure B.3.5). In view of a transition towards a circular economy, it is essential to consider recycling scenarios in the future.

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

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

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

So far, our study considers four metals. Thus, the completeness of prospective LCAs can be increased by adding supply scenarios for more metals, such as steel, aluminum, manganese (Hertwich et al., 2015; van der Voet et al., 2018), lithium (Mohr et al., 2012; Stamp et al., 2012), or cobalt (Tisserant & Pauliuk, 2016).

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

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

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

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

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

3.5. Conclusions

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

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

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

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

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

References

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

Arvesen, Anders, Luderer, Gunnar, Pehl, Michaja, Bodirsky, Benjamin Leon, & Hertwich, Edgar G. (2018). Deriving life cycle assessment coefficients for application in integrated assessment modelling. *Environmental Modelling and Software*, *99*, 111–125. https://doi.org/10.1016/j.envsoft.2017.09.010

Arvidsson, Rickard, Tillman, Anne-Marie, Sandén, Björn A., Janssen, Matty, Nordelöf, Anders, Kushnir, Duncan, & Molander, Sverker. (2017). Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA. *Journal of Industrial Ecology*, *22*(6), 1286–1294. https://doi.org/10.1111/jiec.12690

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

Bauer, Christian, Hofer, Johannes, Althaus, Hans Jörg, Del Duce, Andrea, & Simons, Andrew. (2015). The environmental performance of current and future passenger vehicles: Life Cycle Assessment based on a novel scenario analysis framework. *Applied Energy*, *157*, 871–883. https://doi.org/10.1016/j.apenergy.2015.01.019

Berger, Markus, Sonderegger, Thomas, Alvarenga, Rodrigo, Bach, Vanessa, Cimprich, Alexander, Dewulf, Jo, Frischknecht, Rolf, Guinée, Jeroen, Helbig, Christoph, Huppertz, Tom, et al. (2020). Mineral resources in life cycle impact assessment: Part II–

recommendations on application-dependent use of existing methods and on future method development needs. *The International Journal of Life Cycle Assessment*, 1–16. https://doi.org/10.1007/s11367-020-01737-5

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

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

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

Bruckner, T., Bashmakov, I. A., Mulugetta, Y., Chum, H., Vega Navarro, A. de la, Edmonds, J., Faaij, A., Fungtammasan, B., Garg, A., Hertwich, E., Honnery, D., Infield, D., Kainuma, M., Khennas, S., Kim, S., Nimir, H. B., Riahi, K., Strachan, N., Wiser, R., & Zhang, X. (2014). Energy systems. In *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change* (pp. 5–1). Cambridge University Press, Cambridge, United Kingdom; New York, NY, USA.

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

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

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

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

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

Deetman, Sebastiaan, Pauliuk, Stefan, van Vuuren, Detlef, van der Voet, Ester, & Tukker, Arnold. (2018). Scenarios for demand growth of metals in electricity generation technologies, cars and electronic appliances. *Environmental Science & Technology*, acs.est.7b05549. https://doi.org/10.1021/acs.est.7b05549

Ecoinvent Center. (2018). *Ecoinvent database (version 3.5, allocation, cut-off by classification)*.

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

Elshkaki, Ayman, Graedel, T. E., Ciacci, Luca, & Reck, Barbara K. (2018). Resource Demand Scenarios for the Major Metals. *Environmental Science and Technology*, *52*(5), 2491–2497. https://doi.org/10.1021/acs.est.7b05154

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

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

Fricko, Oliver, Havlik, Petr, Rogelj, Joeri, Klimont, Zbigniew, Gusti, Mykola, Johnson, Nils, Kolp, Peter, Strubegger, Manfred, Valin, Hugo, Amann, Markus, Ermolieva, Tatiana, Forsell, Nicklas, Herrero, Mario, Heyes, Chris, Kindermann, Georg, Krey, Volker, McCollum, David L., Obersteiner, Michael, Pachauri, Shonali, … Riahi, Keywan. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, *42*, 251–267. https://doi.org/10.1016/J.GLOENVCHA.2016.06.004

Gibon, Thomas, Arvesen, Anders, & Hertwich, Edgar G. (2017). Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. *Renewable and Sustainable Energy Reviews*, *76*(July 2016), 1283–1290. https://doi.org/10.1016/j.rser.2017.03.078

Gibon, Thomas, Wood, Richard, Arvesen, Anders, Bergesen, Joseph D., Suh, Sangwon, & Hertwich, Edgar G. (2015). A Methodology for Integrated, Multiregional Life Cycle Assessment Scenarios under Large-Scale Technological Change. *Environmental Science and Technology*, *49*(18), 11218–11226. https://doi.org/10.1021/acs.est.5b01558

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

Graedel, Thomas E., & van der Voet, Ester. (2010). *Linkages of Sustainability* (p. 10). Cambridge, MA: MIT Press.

Harpprecht, Carina, Oers, Lauran van, Northey, Stephen A., Yang, Yongxiang, & Steubing, Bernhard. (2021). *Scenario data for article: Environmental impacts of key metals' supply and low-carbon technologies are likely to decrease in the future*. https://doi.org/10.5281/zenodo.4785135

Hertwich, E., Gibon, Thomas, Bouman, Evert A., Arvesen, Anders, Suh, Sangwon, Heath, Garvin A., Bergesen, Joseph D., Ramirez, Andrea, Vega, Mabel I., & Shi, Lei. (2015). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(20), 6277–6282.

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

International Copper Study Group. (2018). *ICSG 2018 statistical yearbook* (December; Vol. 15). International Copper Study Group.

IPCC. (2013). *Climate Change 2013 - The Physical Science Basis* (p. 1535). Cambridge University Press, Cambridge, United Kingdom; New York, NY, USA. https://doi.org/10.1017/cbo9781107415324

ISO. (2006). *14040-2006 International Standard. Environmental management - Life cycle assessment - Requirements and Guidelines*.

Kleijn, René, van der Voet, Ester, Kramer, Gert Jan, Oers, Lauran van, & Giesen, Coen van der. (2011). Metal requirements of low-carbon power generation. *Energy*, *36*(9), 5640–5648. https://doi.org/10.1016/J.ENERGY.2011.07.003

Kuipers, Koen J. J., Oers, Lauran F. C. M. van, Verboon, Miranda, & van der Voet, Ester. (2018). Assessing environmental implications associated with global copper demand and supply scenarios from 2010 to 2050. *Global Environmental Change*, *49*(February), 106–115. https://doi.org/10.1016/j.gloenvcha.2018.02.008

Kulczycka, Joanna, Lelek, Å�ukasz, Lewandowska, Anna, Wirth, Herbert, & Bergesen, Joseph D. (2016). Environmental Impacts of Energy-Efficient Pyrometallurgical Copper Smelting Technologies: The Consequences of Technological Changes from 2010 to 2050. *Journal of Industrial Ecology*, *20*(2), 304–316. https://doi.org/10.1111/jiec.12369

Le Blanc, David. (2015). Towards Integration at Last? The Sustainable Development Goals as a Network of Targets. *Sustainable Development*, *23*(3), 176–187. https://doi.org/10.1002/sd.1582

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

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

Mendoza Beltran, Angelica, Cox, Brian, Mutel, Chris, van Vuuren, Detlef P., Font Vivanco, David, Deetman, Sebastiaan, Edelenbosch, Oreane Y., Guinée, Jeroen, & Tukker, Arnold. (2020). When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12825

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

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

Mudd, G. M., & Jowitt, S. M. (2014). A Detailed Assessment of Global Nickel Resource Trends and Endowments. *Economic Geology*, *109*(7), 1813–1841.

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

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

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

Mutel, Chris. (2017a). Brightway: An open source framework for Life Cycle Assessment. *The Journal of Open Source Software*, *2*(12). https://doi.org/10.21105/joss.00236

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

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

Mutel, Chris, & Vandepaer, Laurent. (2019). *Wurst examples repository*. https://github.com/IndEcol/wurst-examples

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

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

Norgate, Terry, & Jahanshahi, Sharif. (2006). *Energy and greenhouse gas implications of deteriorating quality ore reserves*.

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

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

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

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

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

Northey, Stephen A., Mudd, G. M., & Werner, T. T. (2018). Unresolved Complexity in Assessments of Mineral Resource Depletion and Availability. *Natural Resources Research*, *27*(2), 241–255. https://doi.org/10.1007/s11053-017-9352-5

Nuss, Philip, & Eckelman, Matthew J. (2014). Life Cycle Assessment of Metals: A Scientific Synthesis. *PLoS ONE*, *9*(7), e101298. https://doi.org/10.1371/journal.pone.0101298

O'Neill, Brian C., Kriegler, Elmar, Riahi, Keywan, Ebi, Kristie L., Hallegatte, Stephane, Carter, Timothy R., Mathur, Ritu, & van Vuuren, Detlef P. (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, *122*(3), 387–400. https://doi.org/10.1007/s10584-013-0905-2

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

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

Pauliuk, Stefan, Majeau-Bettez, Guillaume, Mutel, Christopher L., Steubing, Bernhard, & Stadler, Konstantin. (2015). Lifting Industrial Ecology Modeling to a New Level of Quality and Transparency: A Call for More Transparent Publications and a Collaborative Open Source Software Framework. *Journal of Industrial Ecology*, *19*(6), 937–949. https://doi.org/10.1111/jiec.12316

PBL. (2019). *IMAGE Integrated Model to Assess the Global Environment. Download*. https://models.pbl.nl/image/index.php/Download_packages

Pesonen, Hanna-Leena, Ekvall, Tomas, Fleischer, Giinter, Jahn, Christina, Klos, Zbigniew S., Rebitzer, Gerald, Sonnemann, Guido W., Tintinelli, Alberto, Weidema, Bo P., WenzeF, Henrik, & Weidema, Bo. (2000). Framework for Scenario Development in LCA. *Int J Life Cycle Assessment*, *5*(1), 21–30.

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

Riahi, K., Vuuren, Detlef P. van, Kriegler, Elmar, Edmonds, Jae, O'Neill, Brian C., Fujimori, Shinichiro, Bauer, Nico, Calvin, Katherine, Dellink, Rob, Fricko, Oliver, Lutz, Wolfgang, Popp, Alexander, Cuaresma, Jesus Crespo, KC, Samir, Leimbach, Marian, Jiang, Leiwen, Kram, Tom, Rao, Shilpa, Emmerling, Johannes, … Tavoni, Massimo. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. https://doi.org/10.1016/J.GLOENVCHA.2016.05.009

Roelich, Katy, Dawson, David A., Purnell, Phil, Knoeri, Christof, Revell, Ruairi, Busch, Jonathan, & Steinberger, Julia K. (2014). Assessing the dynamic material criticality of infrastructure transitions: A case of low carbon electricity. *Applied Energy*, *123*, 378–386. https://doi.org/10.1016/j.apenergy.2014.01.052

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

Sandén, Björn A. (2007). Standing the Test of Time: Signals and Noise From Environmental Assessments of Energy Technologies. *MRS Proceedings*, *1041*, 05–06. https://doi.org/10.1557/PROC-1041-R05-06

Sonderegger, Thomas, Berger, Markus, Alvarenga, Rodrigo, Bach, Vanessa, Cimprich, Alexander, Dewulf, Jo, Frischknecht, Rolf, Guinée, Jeroen, Helbig, Christoph, Huppertz, Tom, et al. (2020). Mineral resources in life cycle impact assessment—part i: A critical review of existing methods. *The International Journal of Life Cycle Assessment*, 1–14. https://doi.org/10.1007/s11367-020-01736-6

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

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

Steubing, Bernhard, Koning, Daniel de, Haas, Adrian, & Mutel, Christopher Lucien. (2020). The activity browser—an open source LCA software building on top of the brightway framework. *Software Impacts*, *3*.

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

Tisserant, Alexandre, & Pauliuk, Stefan. (2016). Matching global cobalt demand under different scenarios for co-production and mining attractiveness. *Journal of Economic Structures*, *5*(4). https://doi.org/10.1186/s40008-016-0035-x

Tokimatsu, Koji, Höök, Mikael, McLellan, Benjamin, Wachtmeister, Henrik, Murakami, Shinsuke, Yasuoka, Rieko, & Nishio, Masahiro. (2018). Energy modeling approach to the global energy-mineral nexus: Exploring metal requirements and the well-below 2 °C target with 100 percent renewable energy. *Applied Energy*, *225*(April), 1158–1175. https://doi.org/10.1016/j.apenergy.2018.05.047

UNEP. (2007). *Global Environment Outlook GEO 4: environment for development United Nations Environment Programme*. UNEP.

UNEP. (2013). *Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles, A Report of the Working Group on the Global Metal Flows to the International Resource Panel.* (E. van der Voet, R. Salminen, M. Eckelman, G. Mudd, T. Norgate, & R. Hischier, Eds.). UNEP. https://doi.org/10.1227/01.NEU.0000108643.94730.21

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

van der Voet, Ester, van Oers, Lauran, Verboon, Miranda, & Kuipers, Koen. (2018). Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12722

van Vuuren, Detlef P., Stehfest, Elke, Gernaat, David E. H. J., Doelman, Jonathan C., Berg, Maarten van den, Harmsen, Mathijs, Boer, Harmen Sytze de, Bouwman, Lex F., Daioglou, Vassilis, Edelenbosch, Oreane Y., Girod, Bastien, Kram, Tom, Lassaletta, Luis, Lucas, Paul L., Meijl, Hans van, Müller, Christoph, Ruijven, Bas J. van, Sluis, Sietske van der, & Tabeau, Andrzej. (2017). Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, *42*, 237–250. https://doi.org/10.1016/j.gloenvcha.2016.05.008

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

Wernet, Gregor, Bauer, Christian, Steubing, Bernhard, Reinhard, Jürgen, Moreno-Ruiz, Emilia, & Weidema, Bo. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

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

4 Decarbonization scenarios for the iron and steel industry in context of a sectoral carbon budget: Germany as a case study

This chapter has been published as:

Harpprecht, C., Naegler, T., Steubing, B., Tukker, A., & Simon, S. (2022). Decarbonization scenarios for the iron and steel industry in context of a sectoral carbon budget: Germany as a case study. *Journal of Cleaner Production*, *380*, 134846. https://doi.org/10.1016/j.jclepro.2022.134846

The supplementary information is available at:

https://www.sciencedirect.com/science/article/pii/S0959652622044195#appsec1

Abstract

CO_2 emissions from global steel production may jeopardize climate goals of 1.5°C unless current steel production practices will be rapidly decarbonized. At present, primary iron and steel production is still heavily dependent on fossil fuels, primarily coke. This study aims to determine which decarbonization pathways can achieve the strongest emission reductions of the iron and steel industry in Germany by 2050. Moreover, we estimate whether the German iron and steel industry will be able to stay within its sectoral carbon budgets for a 1.5°C or 1.75°C target. We developed three decarbonization scenarios for German steel production: an electrification, coal-exit, and a carbon capture and storage (CCS) scenario. They describe a phase-out of coal-fired production plants and an introduction of electricity-based, low-carbon iron production technologies, i.e. hydrogen-based direct reduction and electrowinning of iron ore. The scenarios consider the age and lifetimes of existing coal-based furnaces, the maturity of emerging technologies, and increasing recycling shares. Based on specific energy requirements and reaction-related emissions per technology, we calculated future CO_2 emissions of future steel production in Germany. We found that under the decarbonization scenarios, annual CO_2 emissions decrease by up to 83% in 2050 relative to 2020. The reductions of cumulative emissions by 2050 range from 24% (360 Mt CO_2) under the electrification scenario up to the maximum of 46% (677 Mt CO_2) under the CCS scenario compared to a reference scenario. This clearly demonstrates that the technology pathway matters. Nevertheless, the German steel sector will exceed its sectoral CO_2 budget for a 1.5°C warming scenario between 2023 and 2037. Thus, drastic measures are required very soon to sufficiently limit future CO_2 emissions from German steel production, such as, a rapid decarbonization of the electricity mix, the construction of a hydrogen and CCS infrastructure, or early shutdowns of current coal-based furnaces.

4.1. Introduction

Studies have shown that CO_2 emissions due to global steel production will jeopardize the 1.5°C climate target unless steel production is rapidly decarbonized through low-emission production technologies (Tong et al., 2019; Wang et al., 2021).

Of all metals, steel production is responsible for the highest greenhouse gas emissions (GHG), i.e. 9% of global emissions (Nuss & Eckelman, 2014; Wang et al., 2021). As steel is required for buildings, infrastructure, and technologies, it is a key metal for modern societies. Consequently, its demand is expected to increase due to the future industrialization of developing countries (Elshkaki et al., 2018; van Ruijven et al., 2016). Therefore, studies stress the need to develop and implement low-emission technology alternatives for the currently coal-fired primary production (Arens et al., 2017; Ryan et al., 2020; Tong et al., 2019).

The largest steel producer in Europe is Germany, ranking seventh worldwide (WSA, 2020). In Germany as well as globally, the majority of steel is produced via primary production, around 70%, while secondary production accounts for about 30% (WSA, 2019b, 2020). Primary steel is commonly produced via the blast furnace and basic oxygen furnace route (BF-BOF), which mainly uses coke as energy carrier and therefore has a very high emission intensity of 1.6 to 2.2 t CO_2/t steel (Hasanbeigi et al., 2014; Toktarova et al., 2020).

Previous research has shown that the commonly used BF-BOF route can barely be decarbonized (Madeddu et al., 2020) as it requires very high temperatures of up to 2000°C (de Beer et al., 2000; Hasanbeigi et al., 2014). The only other mature process currently being applied is natural gas-based direct reduction (NG-DRI). NG-DRI has a lower emission-intensity than the BF, but it is not widely deployed as natural gas is in most countries not cost-competitive with coke (Moya & Pardo, 2013). Retrofitting BF-BOFs with post-combustion carbon capture and storage (BF-BOF-CCS) can reduce emissions by up to 60% (IEAGHG, 2013), yet this is insufficient for the long-term targets.

Thus, in the case of primary steel production a significant CO_2 reduction can only be achieved through a switch to different technologies. For a deep emission reduction, the key strategy is electrification (de Coninck et al., 2018; Lord, 2018; Madeddu et al., 2020; Philibert, 2017). The technologies considered most promising are hydrogen-based direct reduction (H2-DRI) and electrolysis of iron ore (Fischedick et al., 2014; Lechtenböhmer et al., 2016; Philibert, 2017; Weigel et al., 2016). H2-DRI enables an indirect electrification through hydrogen from water electrolysis, and iron electrolysis allows for a direct electrification of primary steel production.

Hydrogen-based direct reduction (H2-DRI) can be almost CO_2 emission-free if operated with hydrogen from renewable electricity (Fischedick et al., 2014). H2-DRI is often considered the most suitable technology for the near future, as it can be adapted from the already existing technology of natural gas-based DRI (NG-DRI). Direct reduction furnaces can be operated with a mix of natural gas and hydrogen (de Beer et al., 2000). Thus, DRI enables a transition from natural gas to hydrogen in the same furnaces, once enough hydrogen is available (Bhaskar et al., 2020). In Germany, various steel producers plan to implement H2-DRI facilities, e.g. Salzgitter, ArcelorMittal or Thyssenkrupp (Ruhwedel, 2020; Agora Energiewende & AFRY Management Consulting, 2021).

A less mature alternative, yet directly electrified technology, is electrolysis of iron ore. It applies electricity to reduce iron ore and thus avoids the conversion losses during hydrogen production, that occur in the case of H2-DRI. Two types of electrolysis are at pilot stage: first, electrowinning (EW) in a low-temperature (110°C) alkaline solution (Yuan et al., 2009) with a pilot plant in France under the SIDERWIN project (IEA, 2020a; Lavelaine, 2019); secondly, using high-temperature molten oxide with a temperature of 1600°C (Ryan et al., 2020). This type using high temperatures is considered less mature than the electrowinning at lower temperatures (Hasanbeigi et al., 2014).

For more information on current and future steel production technologies, the reader is referred to the existing literature, such as Zhang et al. (2021), Wang et al. (2021), or IEA (2020a).

The German Federal Ministry for Economic Affairs and Climate Action (BMWK, former BMWi) considers NG-DRI for the very near future with a transition to H2-DRI for the long-term as key technologies for a decarbonization of primary steel production according to its Steel Action Concept (BMWi 2020), yet it does not propose concrete transition pathways. Germany's Climate Protection plan suggests implementing CCS to address unavoidable emissions in industry and to reach GHG reductions of 95% by 2050 (BMU, 2016).

Many previous studies investigated emission-reduction potentials of different technologies individually (Bhaskar et al., 2020; Hasanbeigi et al., 2014; Otto et al., 2017; Tian et al., 2018; Vogl et al., 2018; Zhang et al., 2021). Amongst these only a few consider the novel technology of electrolysis of iron (Fischedick et al., 2014; Lechtenböhmer et al., 2016; Weigel et al., 2016).

Some studies model regional transformation pathways, e.g. for Sweden (Toktarova et al., 2020) or the US (Ryan et al., 2020), and investigate their emission reduction potential by a certain target year. Arens et al. (2017) calculated potential future CO_2 emissions from German steel production by 2035 considering amongst others the technologies of NG-DRI or smelting reduction, which replaces coke with pulverized coal (Zhang et al., 2021). They found that the emission-intensities of these technologies are still too high to reach climate goals. Therefore, they recommend the inclusion of more technology alternatives, such as H2-DRI or electrolysis of iron ore.

Other studies developed transformation pathways for the steel industry and compared their future *cumulative* emissions to a global carbon budget. Tong et al. (2019) show that emissions of currently existing industrial plants alone will exhaust the entire global carbon budget for a 1.5°C scenario, if operated until their average end-of-life. Wang et al. (2021) estimated future cumulative emissions by 2050 from the global steel industry under scenarios for efficiency improvements. Even their strictest efficiency scenarios would exceed a sectoral 1.5°C budget for the steel sector by more than 100%, if the global budget was distributed to sectors based on current emission shares. Similarly, Ryan et al. (2020) stress that immediate action is required for the steel industry in the US to achieve a linear reduction of emissions by 70% by 2050.

Research to date has not yet determined decarbonization pathways for the iron and steel industry in Germany to stay within the sector's carbon budget, considering the deployment of both indirectly and directly electrified primary production technologies, such as electrowinning of iron ore. This study aims to answer the following two research questions:

1. *Which technology pathways can achieve the strongest decarbonization of the iron and steel industry in Germany by 2050 and what are their implications in terms of future final energy demand?*
2. *To which extent may the German iron and steel industry be able to stay within its sectoral carbon budget for a 1.5°C target?*

In this study, we developed three decarbonization scenarios for steel production with the goal to phase out fossil fuels-based furnaces and to achieve a primarily electricity-based steel production by 2050. The scenarios model the replacement of currently existing BFs in Germany with directly and indirectly electrified production technologies, such as electrowinning and H2-DRI. To calculate future CO_2 emissions, we developed process models for energy consumption and reaction-related emissions of six steel production routes. We compared the resulting emissions with carbon budgets, which we allocated to the sector from carbon budgets for Germany (see section 4.2.4).

The results can inform decision-makers which technology pathway may be most efficient to minimize future CO_2 emissions from the iron and steel industry in Germany. Moreover, they reveal implications for the energy system and infrastructure requirements, for example, in terms of future demand for hydrogen, electricity or carbon storage facilities.

4.2. Material and methods

4.2.1. Process models for current and future steel production routes

We developed a process model to calculate current and future CO_2 emissions from steel production in Germany considering six different steel production routes (see Figure 1). Three of them are current practice, these are the blast furnace and basic oxygen furnace (BF-BOF), natural gas-based direct reduction (NG-DRI), and the scrap-based electric arc furnace (scrap-EAF) routes. Two technology routes represent low-carbon, electrified technologies for iron production: the hydrogen-based direct reduction (H2-DRI) for indirect electrification and electrowinning (EW) for direct electrification. They are followed by the electric arc furnace (EAF) to refine iron to steel. The BF-BOF-CCS route applies post-combustion carbon capture and storage (CCS) to the BF-BOF route.

Using data from literature, we modelled process-specific energy requirements and derived CO_2 emissions for each route, i.e. energy- and reaction-related CO_2 emissions (see section 4.2.3). The specific energy demand of existing technologies was calibrated using energy statistics for the steel sector for the year 2018 (Rohde, 2019).

The model describes the steel production chain from raw material preparation, e.g. sinter or pellet production from iron ore, up to the steel market. Mining of iron ore is excluded. The main characteristics and assumptions for each production route are given in Table 1. The complete dataset is provided in a repository (Harpprecht et al., 2022).

The BF-BOF route is a highly integrated system, which reuses flue gases from different ovens (BF, BOF, and CO gas) (Remus et al., 2013). Our model takes this into account including on-site power generation from these gases.

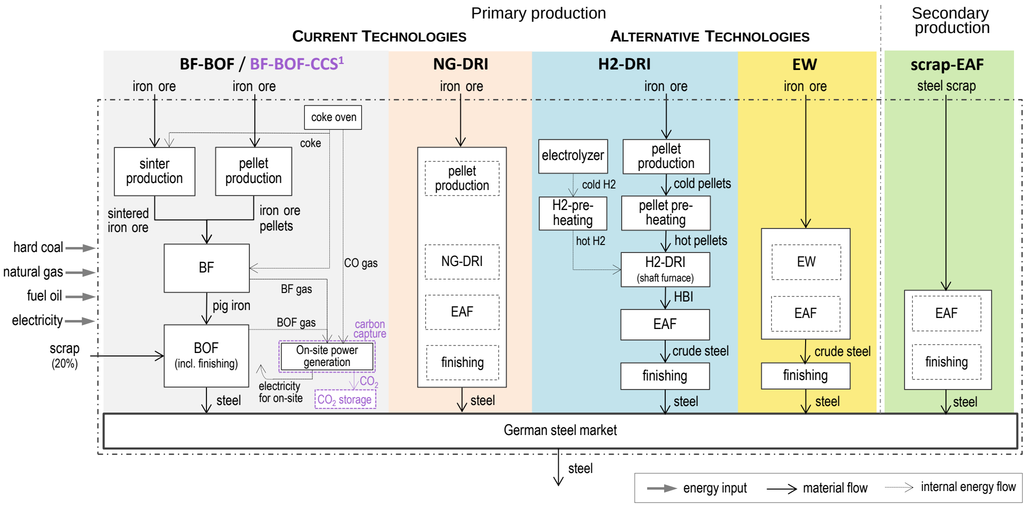


Figure 1: Process model of the six steel production routes considered. For the BF-BOF route, on-site power generation from process gases is included in the system. For the BF-BOF-CCS route, post-combustion carbon capture is applied to the on-site power plant. BF-BOF = blast-furnace and basic-oxygen furnace; BF gas = blast-furnace gas; BOF gas = basic-oxygen furnace gas; CCS = carbon capture and storage; CO gas = coke oven gas; EW = electrowinning; H2-DRI = hydrogen-based direct reduction; NG-DRI = natural gas-based direct reduction; scrap-EAF = scrap-based electric arc furnace. [1]: BF-BOF-CCS is illustrated here within the current technology of BF-BOF due to space restrictions, but it is technically also an alternative technology.

For the BF-BOF-CCS, we assumed that post-combustion carbon capture facilities are deployed at the on-site power plant to clean the flue gases (Chisalita et al., 2019). Additional electricity and steam required for the carbon capture facility are produced on-site in the gas-fired power plant and increase its natural gas consumption. Carbon transport and storage, i.e. CO_2 compression and injection require additional electricity from the grid (15.65 kWh/t steel). We assume transport in pipelines over 800 km and storage in the North Sea based on Chisalita et al. (2019). Losses of CO_2 from CCS are neglected, as they amount to less than 0.2% of CO_2 captured according to Chisalita et al. (2019). In this study, we consider CCS for BF-BOFs only as an interim and not a long-term solution. It should only be applied on already existing fossil fuel-based furnaces to reduce their emissions until they can be replaced by electrified technologies in the future.

The developed process model is implemented in the Activity Browser, an open-source software, which was used to calculate the final energy demand and emissions (Steubing et al., 2020). The python code for this can be found in our repository (Harpprecht et al., 2022).

Table 1: Description and used data sources for the modeled steelmaking technologies. The complete dataset is provided in the repository (Harpprecht et al., 2022).

Technology	**BF-BOF**	**BF-BOF-CCS**	**NG-DRI**	**H2-DRI**	**EW**	**Scrap-EAF**
Name	Blast furnace and basic oxygen furnace	BF-BOF with post-combustion carbon capture and storage (CCS)	Natural gas-based direct reduction	Hydrogen-based direct reduction	Electrowinning	Steel scrap recycling in electric arc furnace
Main energy carrier	coal	coal	natural gas	electricity for H2 from water electrolysis	electricity	electricity
Market shares[1]	70%	0%	1.2%	0%	0%	28.8%
TRL [2]	9	>5[7]	9	5-7[3]	4-6	9
Assumed year of market entry	-	2025[6]	-	2025[4]	2040[5]	-
Data source for energy demand	Remus et al. (2013)	IEAGHG (2013), Chisalita et al. (2019)	Arens et al. (2017)	Bhaskar et al. (2020), Worrell et al. (2007)	Fischedick et al. (2014), Worrell et al. (2007)	Arens et al. (2017)
Details and assumptions	Integrated system with on-site power generation from flue gases. No export of flue gases or other energy carriers. Scrap is added to BOF (20% of input into BOF, see section B.2.3).	Carbon capture (CC) technology is chemical absorption with mono-ethanol amine. Additional electricity and steam for CC are produced on-site from additional natural gas, i.e. 3.36 GJ NG/t steel. CCS reduces emissions of current BF-BOF by 50%.	Bridging technology for H2-DRI, as planned by Salzgitter and Arcelor Mittal. Mixtures of natural gas and hydrogen can be applied. Pure hydrogen can be used later without retrofitting (Agora Energiewende & Wuppertal Institut, 2019).	Shaft furnace, e.g. by Midrex (same as existing DRI plant in Hamburg), which can be fed with pellets or lump ore. Varying mixtures of natural gas and hydrogen can be applied.	Electrolysis of iron ore, using a low-temperature (110°C) alkaline solution (Zhang et al., 2021). A TRL of 4 has been achieved by previous projects. The Siderwin project led by ArcelorMittal aims to achieve TRL 6 by 2022 (Lavelaine, 2019).	Some fossil fuels (hard coal and natural gas) are required for the EAF for heat provision. 1.1 t scrap are required to produce 1 t of steel (Remus et al. (2013).

[1]: in DE in 2018 (WV-Stahl, 2019; WSA, 2019a); [2]: Technology readiness level: ranges from 1 (initial idea) to 9 (maturity). From (Agora Energiewende & Wuppertal Institut, 2019; IEA, 2020a; Toktarova et al., 2020; Wang et al., 2021); [3]: if pure hydrogen is used, the TRL is 5. For a mixture with natural gas, the TRL is 7; [4]: (Agora Energiewende & Wuppertal Institut, 2019; Ruhwedel, 2020; Toktarova et al., 2020); [5]: (Fischedick et al., 2014); [6]: (Agora Energiewende & Wuppertal Institut, 2019; IEA, 2020a); [7]: For iron and steel, the TRL for amine-based CO_2 capture is 5 (IEA, 2020a). At power plants, the TRL is already 7-8 (Hills et al., 2016).

4.2.2. Scenario definition: development of technology pathways

We developed a reference scenario, in which current production practices are continued, and three decarbonization scenarios for the German iron and steel industry: an electrification, a coal-exit, and a carbon capture and storage (CCS) scenario. The decarbonization scenarios were derived as explorative pathways which have as an objective to phase out coal- and natural-gas based furnaces and to achieve a primarily electricity-based steel production by 2050. The reference scenario shows a future where electrification cannot be achieved.

The backbone of all scenarios is the future development, specifically the phase-out, of blast furnace capacities in Germany. We assume that only if a BF is shut down, a new technology can enter the market and take over the then available capacity. The phase-out of BFs is modelled using data on capacity and age of each individual BF currently existing in Germany from Arens et al. (2017). The lifetime of the BFs is varied according to the narrative of each scenario, see Table 2. Based on the future capacity of BFs (see section B.2.1 for details), we then modelled the future market shares of the other five production routes in five-year intervals until 2050 with the following constraints and assumptions.

Constraints for all scenarios:

- Total steel production stays constant at 42.4 Mt steel/year as in 2018 (WSA, 2019a). In the past, steel production in Germany has stayed relatively constant (WSA, 2019a). We assume a constant production also for the future since high-income countries require steel mostly for maintaining already existing infrastructure (Brown et al., 2012; Brunke & Blesl, 2014; Mayer et al., 2019). This is different from developing countries, which are expected to have an increasing steel demand in the future to build up completely new infrastructure (Brown et al., 2012).
- Depending on the scenario narrative, BF capacity is replaced with other technologies (see Table 2) but not before the technology-specific year of market entry from Table 1.
- Scrap availability increases by 0.9% per year (Arens et al., 2017) with scrap being input to the BF-BOF, scrap-EAF and, if necessary, to EW. This scrap availability cannot be exceeded by the scrap consumption (see section B.2.3).
- For the decarbonization scenarios: Diffusion of NG-DRI and H2-DRI, i.e. building new furnaces for direct reduction, takes place from 2025 to 2040. After 2040, DRI capacity does not increase anymore, as new capacities are assumed to be realized through EW, which then enters the market. NG-DRI serves as a bridging technology for H2-DRI, until sufficient hydrogen is available in 2040. The diffusion of hydrogen for direct reduction follows a typical s-shape (Hall & Khan, 2002) (see Figure B-2).

Additional assumptions for the three decarbonization scenarios:

- For DRI, varying mixes of natural gas and hydrogen can be applied.
- Hydrogen is produced via electrolysis of water with an efficiency of 74% (Bhaskar et al., 2020).

The narratives and resulting assumptions of the four scenarios are described in Table 2. The electrification scenario forms the baseline of the three decarbonization scenarios, with the coal-exit and CCS scenario being variants of the electrification scenario.

It is important to note that the above-mentioned constraints and assumptions in combination with the objective of reaching a primarily electricity-based steel production by 2050 are sufficient to determine scenarios for future production amounts of each production route in five-year intervals. Based on expert judgment and an explorative modelling approach, we developed plausible pathways, or so-called what-if scenarios, consistent with the constraints and assumptions.

Table 2: Description of the four scenarios modelled for the German iron and steel industry. The average (av.) lifetime of blast furnaces (BFs) is assumed to be 50 years, which can be prolonged by 20 years through relining of the furnaces to reach 70 years (Agora Energiewende & Wuppertal Institut, 2019; Arens et al., 2017).

Scenario	**Description**	**Assumptions for BF lifetimes**	**Technologies replacing BF-BOFs**			
			NG-DRI	**H2-DRI**	**EW**	**BF-BOF-CCS**
Reference	· Continuation of current production practices with the goal of minimizing investment costs. · Low-carbon technologies are not deployed, instead av. lifetimes of BFs are prolonged.	· 70 years · Prolongation of av. lifetime of BFs by 20 years through relining	x			
Electrification	· Efforts are taken to achieve a decarbonization through the deployment of low-emission technologies as soon as they are available.	· 50 years · Av. lifetime with earlier shutdowns of the last BF in 2050 and 2025 as announced by Salzgitter (Ruhwedel, 2020).	x	x	x	
Coal-exit	· Variant of electrification scenario but with an earlier shutdown of all BFs in 2038. · Aligned to the goal in Germany to achieve an early coal-exit of coal-fired power plants in 2038.	· 50 years · as electrification scenario, but not beyond 2038	x	x	x	
Carbon capture and storage (CCS)	· Variant of electrification scenario adding CCS. · CCS is deployed in 2025 for BFs which will still have a lifetime of at least 10 years.	· 50 years · (as electrification scenario)	x	x	x	x

4.2.3. Calculation of CO_2 emissions

We calculate CO_2 emissions based on the energy requirements defined in the process model (see section 4.2.1) and the future production amounts per production route (see derivation in section 4.2.2). We determine both energy-related and reaction-related CO_2 emissions during steel production. Our analysis focusses on CO_2 as it is the most relevant GHG (Ryan et al., 2020): for energy-related emissions it accounts for 98.8% and for reaction-related for 100% of GHG emissions from steel production (Otto et al., 2017).

Energy-related emissions

We define energy-related CO_2 emissions as emissions caused by the application of energy carriers for energy provision or as reducing agents. Thus, they are related to fuel and electricity usage. For fuels, we consider direct emissions using constant emission factors (see Table 3).

For electricity, we apply time-dependent emission factors of the average German electricity mix (see Table 4) considering minimum and maximum values. Those are derived from an energy scenario comparison from Naegler et al. (2021), who assessed ten energy transformation pathways for Germany, ranging from 80% to 95% emission reduction goals by 2050 (see Figure B-4). This range of electricity emission factors is applied to all scenarios to explore respective ranges of future emissions from steel industry.

Table 3: Emission factors of energy carriers to calculate direct energy-related CO_2 emissions from fuel usage (source: Arens et al. (2017), Umweltbundesamt (2020)).

Energy carrier	Emission factor in kg CO_2/GJ
hard coal	93.1
fuel oil	79.9
natural gas	55.7
CO gas, BF gas, BOF gas[1]	0

[1]: For coke oven gas (CO gas), blast furnace (BF) gas and basic oxygen furnace (BOF) gas, emission factors are assumed to be 0, as they contain CO_2 from the fuels used or from chemical reactions, which are already accounted for by the fuel usage or by the reaction-related emissions (Climate Leaders, 2003).

Table 4: Assumed direct CO_2 emissions for the German electricity mix in kg CO_2/GJ (calculated from Naegler et al. (2021)). Minimum and maximum values are taken from ten different electricity scenarios for Germany with emission reduction goals of 80% or more by 2050. They are applied to all steel scenarios.

	2018	2020	2025	2030	2035	2040	2045	2050
Min	124.9[1]	112.3	103.5	68.7	39.4	17.4	9.7	1.1
Max		114.0	109.7	85.8	63.1	45.4	30.2	20.4

[1]: average value

Reaction-related emissions

Reaction-related CO_2 emissions were modeled based on data from literature (see section B.3.2 for details). They occur in the EAF, e.g. due to the electrode burn-off, and in the BF and the BOF, due to the reaction of calcining limestone, which is added to remove impurities.

4.2.4. Definition of a sectoral carbon budget for the iron and steel industry in Germany

Carbon budgets for Germany

The IPCC determined global carbon budgets from the year 2020 onwards for different temperature increases, e.g. 400-500 Gt CO_2 for a climate goal of 1.5°C (67th and 50th percentile) (IPCC, 2021). Different approaches exist to distribute the global carbon budget among nations, each having some shortcomings regarding international and intergenerational justice (Gignac & Matthews, 2015; Neumayer, 2000; Raupach et al., 2014; Robiou du Pont & Meinshausen, 2018; Stott, 2012). The grandfathering approach uses current shares of global emissions, while the equal per capita approach applies the respective national share of the global population (Neumayer, 2000). A compromise between these two is the contraction & convergence approach, where national emissions converge to a global equal per capita value in a convergence year, e.g. in 2035, and then follow the same equal per capita trajectory (Meyer, 2000). To date, shares by country and sector have not officially been decided (Matthews et al., 2020).

For a national carbon budget for Germany, we collected different suggestions from literature (see Table 5). This leads to a range of 2.5-7.9 Gt CO_2 for the 1.5°C target and 6.7-9.3 Gt CO_2 for the 1.75°C target.

Table 5: Suggested carbon budgets for Germany from different sources for different distribution approaches. The budgets are for January 2020 onwards.

Climate target	Distribution approach	Source	Per-centile	Amount	Unit
1.5°C	equal per capita	**SRU (2020)**	50th	4.2	Gt CO_2
		Wuppertal Institut (2020)	67th	2.5	Gt CO_2
	grandfathering	**Mengis et al. (2021)[1]**	50th	7.9	Gt CO_2
		Mengis et al. (2021)[1]	67th	4.2	Gt CO_2
	contraction & convergence	**Mengis et al. (2021)[1]**	-[2]	7.6	Gt CO_2
1.75°C	equal per capita	**Wuppertal Institut (2020)**	50th	9.3	Gt CO_2
		SRU (2020)	67th	6.7	Gt CO_2

[1]: adapted by subtracting emissions of Germany in 2018 and 2019 from UNFCCC (2021).

[2]: for the contraction & convergence approach, it is not possible to specify uncertainties as it is derived from an emission trajectory based on current emissions, the convergence year and the global equal per capita emissions.

Allocating a sectoral carbon budget to the iron and steel industry

The share of emissions by the steel industry of Germany's total emission has been growing slightly since 1990 from 6% to 8.1% in 2019 (UNFCCC, 2021). To allocate a sectoral carbon budget to the steel industry, we first assume the average share of the last 5 years, i.e. 7.6%, resulting in proportional carbon budgets. Secondly, as it is a hard-to-abate sector (Davis et al., 2018), which might receive a higher share of a carbon budget (SRU, 2020), we also consider an increased share of 10%. This leads to ranges for carbon budgets as shown in Table 6.

Table 6: Ranges of sectoral carbon budgets for the iron and steel industry in Germany from January, 2020, onwards, derived with an average share of 7.6% and an increased share of 10% of the national carbon budgets from Table 5.

Climate target	Average share (proportional) Min	Max	Increased share Max	Unit
1.5°C	0.19	0.60	0.79	Gt CO_2
1.75°C	0.51	0.71	0.93	Gt CO_2

4.3. Results

4.3.1. Emission-intensity of production routes

Figure 2 compares the specific CO_2 emission-intensities of the different production routes. It shows that process alternatives are highly sensitive to power production. If power is decarbonized, the lowest emission-intensities can be achieved by H2-DRI, EW, and scrap-EAF, which are 83%, 86% and 90% lower than for the BF-BOF route. Then, they clearly outperform CCS, i.e. the BF-BOF-CCS route, which achieves an emission reduction by only 50%. In the BF-BOF-CCS route, the emissions due to the increased requirements of electricity for the CCS processes are negligible compared to the overall energy demand and CO_2 emissions of that route (see Figure C-1).

It stands out that DRI purely run on hydrogen, i.e. H2-DRI, currently has a higher emission-intensity than BF-BOF. It might become lower than BF-BOF between 2027 and 2029 (for electricity_min and electricity_max respectively), lower than NG-DRI between 2028-2032, and lower than BF-BOF-CCS between 2036-2043 when power in Germany will become increasingly renewable (90; 79; and 37 kg CO_2/GJ electricity respectively). Emission-intensities of NG-DRI are now already lower than of BF-BOF (-10%) which makes natural gas beneficial to mix with hydrogen in the early years of H2-DRI.

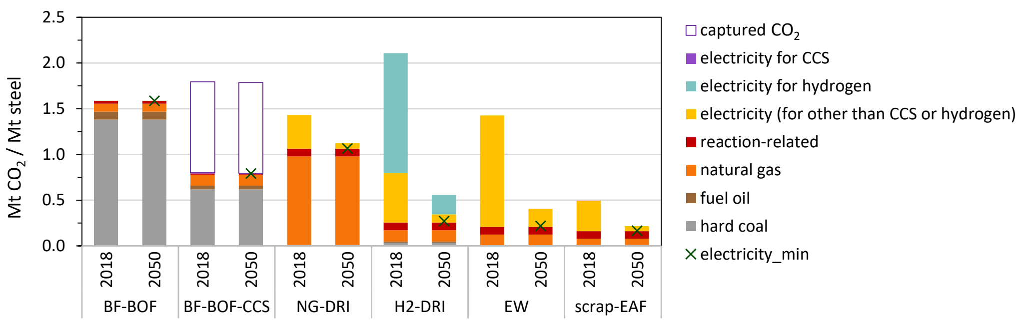


Figure 2: CO_2 emissions per production route considering energy- and reaction-related emissions. For 2018, the average emission factor for electricity is assumed. For 2050, the green cross (electricity_min) shows total emissions if the minimum instead of the maximum emission factor for electricity is assumed (see Table 3 and Table 4 for the assumed emission factors). Emissions caused by the electricity for carbon storage in the BF-BOF-CCS route are so low that they are barely visible in the chart. Energy requirements per route are provided in Figure C-1.

4.3.2. Technology pathways of the decarbonization scenarios

Figure 3 illustrates the technology pathways of each decarbonization scenario to reach electrification by 2050 compared to the reference scenario. In the three decarbonization scenarios (Figure 3.b) – d)), the coal-based BF-BOF is replaced by low-carbon technologies, firstly by NG-DRI, then H2-DRI and from 2040 onwards by EW-EAF. The BF-BOF route is completely phased out by 2050 for the electrification and CCS scenario and by 2038 in case of the coal-exit scenario. For all decarbonization scenarios, the main energy carrier will be electricity by 2050. The new DRI capacity, which is built from 2020 – 2040, serves as a bridging technology from NG-DRI to H2-DRI. The DRIs are firstly run with natural gas but can later switch to hydrogen, when enough green hydrogen is available. In the CCS scenario, CCS is installed in 2025 on still existing BF-BOFs. The share of scrap-EAF increases from 30% in 2020 to up to 57% by 2050.

An analysis describing when investments into new furnace capacities are required in each scenario is provided in section C.5 and Figure C-2 in the supplementary information.

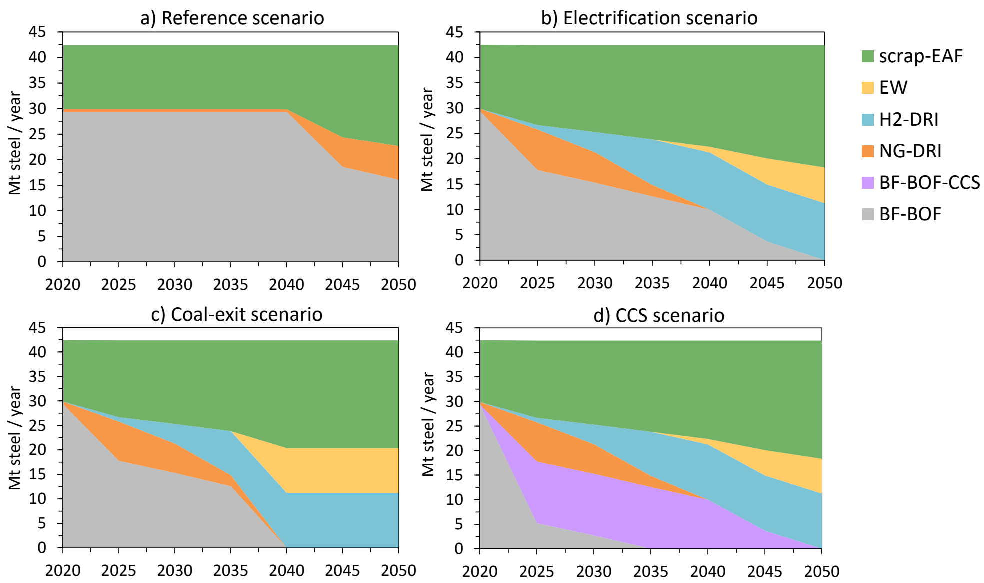


Figure 3: Development of the technology pathways, i.e. the market shares of different steel production technologies, for each scenario. For details on the scenario definition see Table 2, and for the BF-BOF capacities see Figure B-1. Underlying data is supplied in our repository (Harpprecht et al., 2022).

4.3.3. Future energy requirements

Figure 4 illustrates the implications of the decarbonization scenarios in terms of future energy demand. While the decarbonization scenarios lead to similar energy requirements in 2050, they require different developments of energy supply and cumulative future energy demand from 2020 until 2050. Under the decarbonization scenarios, the final energy demand for iron and steel production in Germany decreases by 30% to 33% by 2050 compared to 2020, which is more than double than in the reference scenario (see Figure 4.a) – d)). The reason is that the technologies prevailing in 2050 (EW-EAF and scrap-EAF) are more energy-efficient than the conventional BF-BOF route (see Figure C-1).

In all three decarbonization scenarios, the current primary energy carriers of coke and hard coal are continuously phased out in the future due to the declining share of BF-BOF (see Figure 4.a) – d)). We can see a shift firstly to natural gas and later to electricity and hydrogen. The demand of natural gas peaks in 2025 due to the increasing market share of NG-DRI in all three decarbonization scenarios. The peak for natural gas is the highest in the CCS scenario due to additional natural gas requirements for the carbon capture facilities. After 2025, the demand for natural gas shifts to electricity for hydrogen given the transition from NG-DRI to H2-DRI.

In 2050, all decarbonization scenarios realized a transition to electrification, such that 79 – 80% of the energy demand in 2050 could be covered through electricity. As a result, annual electricity demand increases by a factor of 14 – 15, i.e. from 5.9 TWh/year in 2020 to 83 – 87 TWh/year by 2050. From this, a share of 37% – 39% (32.7 TWh) is required for hydrogen electrolysis to satisfy the demand of 87 PJ of hydrogen (24.2 TWh) in 2050. In 2050, small amounts of natural gas (ca. 70 PJ), fuel oil, and hard coal are still assumed for the pellet production (Remus et al., 2013), finishing of crude steel (Arens et al., 2017; Worrell et al., 2007) and as heat provision for the EAF (Kirschen et al., 2011; Otto et al., 2017) (see Figure C-1).

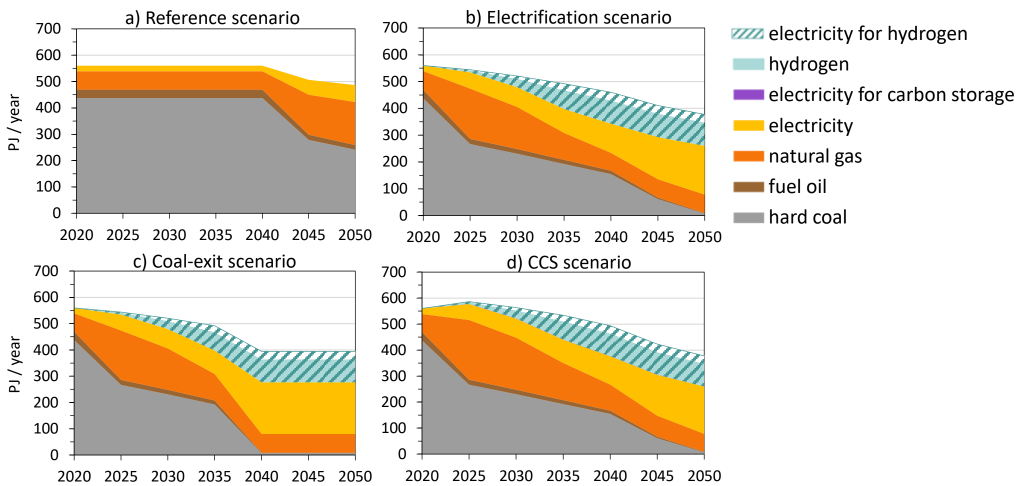


Figure 4: Annual energy demand for iron and steel production per energy carrier for each scenario. The hatched area illustrates the electricity demand to electrolyze hydrogen. The hydrogen demand is shown in blue. Electricity for carbon storage in the CCS scenario is so low that it is not visible in the chart.

4.3.4. Future CO_2 emissions

Figure 5 demonstrates how the resulting CO_2 emissions drastically decrease by 2050 under the decarbonization scenarios, i.e. by up to 83% compared to 2020, while the reference scenario achieves only a 31% emission reduction. The reason is mainly that coke and coal can be replaced by electricity, whose emission factor is assumed to decrease over time and become almost 0 in 2050. Moreover, we can see the large impact of the power sector on an electrified industry: only a very ambitious power sector transformation decreases emissions by up to 83%. With less ambition (maximum electricity emission factor assumed) only about 72% of today's emission can be avoided. In the CCS scenario, 255 Mt CO_2 are assumed to be captured and stored by 2050. Furthermore, it becomes visible that reaction-related emissions from the EAF will gain in relevance in the future. They increase from 2.0 Mt CO_2 (4%) in 2020 to 3.6 Mt CO_2 (24-42%) in 2050.

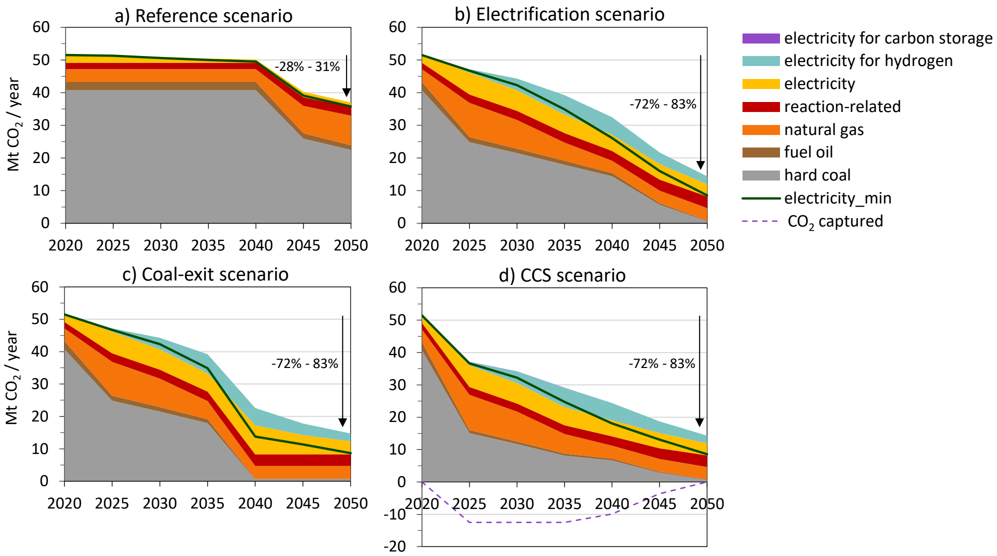


Figure 5: Annual CO_2 emissions into the atmosphere per energy carrier for each scenario. The green line (electricity_min) shows the emissions in 2050 if the minimum instead of the maximum emission factor is assumed for electricity (see Table 3 and Table 4 for the assumed emission factors). The values given in percentage stand for the emission reduction in 2050 compared to 2020 if the maximum and minimum emission factors for electricity are assumed. The captured emissions shown as negative in d) are only provided for reference, this means they are already subtracted respectively from the sum of emissions.

Figure 6 compares the cumulative emissions of the four scenarios with the predefined carbon budgets for the iron and steel industry in Germany. Compared to the reference scenario, all three decarbonization scenarios reduce cumulative emissions considerably by 2050, i.e. by 24% (360 Mt CO_2) in case of the electrification_max scenario to a maximum of 46% (677 Mt CO_2) under the CCS_min scenario. Nevertheless, all decarbonization scenarios exceed the sectoral carbon budgets for both climate targets by up to 490% (electrification_max scenario and min. 1.5°C budget). For the 1.5°C target, the budget may be exceeded between 2023 and 2033 under the electrification and coal-exit scenario, and in

2037 under the CCS scenario. Only the increased budget for the 1.75°C target may be met by some scenarios: the coal-exit_min, CCS_max and the CCS_min scenario. The implementation of CCS considerably reduces emissions, i.e. by up to 206 Mt CO_2 by 2050 compared to the electrification scenario. Within each decarbonization scenario, a more renewable electricity supply reduces cumulative emissions by 10% to 12% (111 to 128 Mt CO_2), which is the difference between the minimum and the maximum emission trajectories.

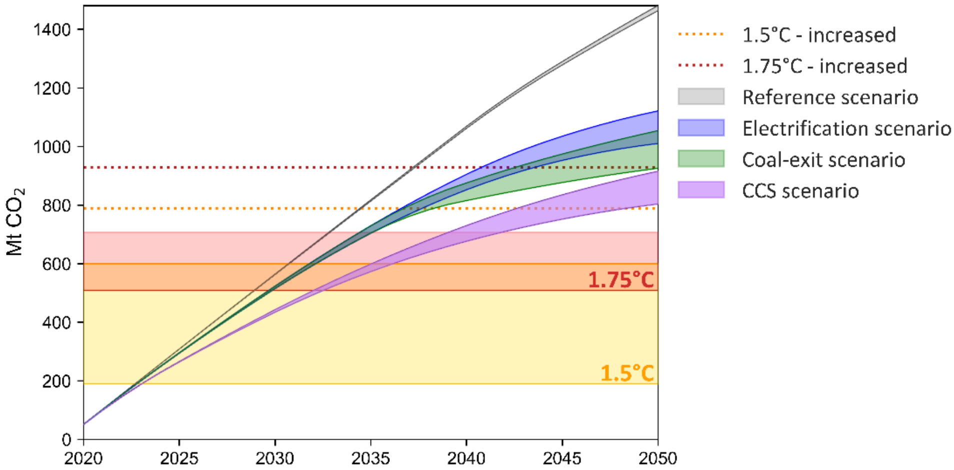


Figure 6: Cumulative CO_2 emissions for 2020-2050 per scenario compared to proportional carbon budgets of the iron and steel industry in Germany for a 1.5°C (yellow area, average share) and a 1.75°C (red area, average share) climate target (for budget definition see Table 6). The dashed horizontal lines represent the carbon budgets if the allocation share for the steel industry is increased from its average of 7.6% to 10%. For each scenario, the emission factor of electricity is varied between minimum and maximum values (see Table 4).

4.3.5. Implications for the future energy supply

Figure 7 compares the future cumulative energy demand for each scenario with their respective cumulative CO_2 emissions from 2020 to 2050. Under the decarbonization scenarios, the cumulative demand for coal decreases by 52–60%, while the demand for natural gas increases by 17-47% and for electricity by a factor of 5.6-6.3 compared to the reference scenario.

Among the decarbonization scenarios, the coal-exit scenario achieves the highest reduction of the cumulative energy demand in total, i.e. by 13%, as well as for fossil fuels, i.e. by 46%, compared to the reference scenario (see Figure 7). The reason is its early phase out of the BF-BOF route. The electrification scenario ranks second with a reduction of 11% in total, while the CCS scenario leads to lowest reduction of 6% of the cumulative energy demand compared to the reference scenario. The reason is that carbon capture increases the cumulative natural gas demand by 26% (0.86 EJ) compared to the electrification scenario (3.32 EJ). Despite its higher energy demand, CCS enables a considerable reduction of cumulative CO_2 emissions, i.e. by 206 Mt CO_2 or 18-20% compared to the electrification scenario.

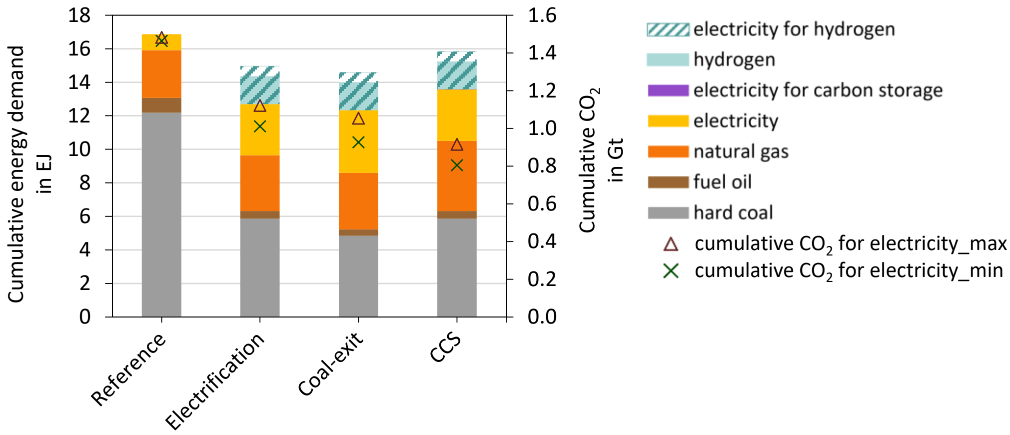


Figure 7: Cumulative energy demand per energy carrier (stacked columns, left axis) compared to cumulative CO_2 emissions (right axis) from 2020 until 2050 for each scenario. The red triangle (electricity_max) and the green cross (electricity_min) show the cumulative CO_2 emissions in 2050 if the maximum or minimum emission factors are assumed for electricity (see Table 3 and Table 4 for the emission factors).

4.4. Discussion

4.4.1. Key findings

This study aimed at comparing the decarbonization potential of different technology pathways of the iron and steel industry in Germany modeled with the help of three decarbonization scenarios: an electrification scenario deploying hydrogen-based DRI (H2-DRI) and electrowinning (EW), as well as two variants thereof, an early coal-exit scenario and a carbon capture and storage (CCS) scenario. We found that the reduction of annual CO_2 emissions by 2050 are very similar across scenarios (72-83%), while their cumulative emissions from 2020 to 2050 differ considerably, as the timing of the strongest emission reductions differs among scenarios. The reductions of cumulative emissions by 2050 range from 24% (360 Mt CO_2) under the electrification scenario up to the maximum of 46% (677 Mt CO_2) under the CCS scenario relative to the reference scenario. This clearly demonstrates that the technology pathway, i.e. the implementation speed and choice of alternative technologies, matters. Moreover, the results showed that the electricity emission factor plays an important role: within each decarbonization scenario, our optimistic trajectory for future emission factors of the power mix reduces cumulative emissions by up to 12% (128 Mt CO_2) (see electricity_min vs. electricity_max in Figure 7, Table 4).

Nevertheless, all three decarbonization scenarios considerably exceed the sectoral carbon budgets, adopted for this study for the German iron and steel industry, not only for the 1.5°C but also for the 1.75°C target up to a factor of almost five.

Additionally, we investigated some implications of the decarbonization scenarios. Maximum emission reduction under the CCS scenario would require storing 255 Mt CO_2 and increase the cumulative natural gas demand by 26% compared to the electrification scenario to run CCS facilities. In all decarbonization scenarios, hard coal is almost completely phased out by 2050, and a shift to primarily electricity-based production is achieved with electricity accounting for about 80% (up to 87 TWh) of the energy demand (see Figure 4). As a result, annual electricity demand rapidly rises by a factor of ca. 15 from 2020 to 2050. From this, up to 39% are required to produce 87 PJ of hydrogen in 2050. Nevertheless, final energy demand decreases in 2050 by up to 33% compared to 2020, as the prevailing technologies of EW and scrap-EAF are more energy-efficient than BF-BOF.

4.4.2. Comparison with previous studies

A comparison of the technology pathways of our study (see Figure 3) with three recent studies on decarbonization scenarios for the German steel industry by 2050 (Purr et al., 2019; Prognos et al., 2020; Robinius et al., 2020) confirms our result that scrap-EAF can supply 52–57% of steel in 2050 (see Table D-1). However, our study is the only one which considers the introduction of electrowinning (EW) from 2040 onwards as well as the interim technology of carbon capture and storage for existing BF-BOFs (BF-BOF-CCS) between 2020 and 2050.

Although a direct comparison of results between studies is not possible due to different system boundaries and process assumptions, a rough comparison illustrates that our emission intensities of production routes (see Figure 2) are within the range of emission intensities reported by previous research (Agora Energiewende & Wuppertal Institut, 2019; Arens et al., 2017; Bhaskar et al., 2020; Chisalita et al., 2019; Fischedick et al., 2014; IEAGHG, 2013; Lösch et al., 2020; Otto et al., 2017) (see Figure D-1). For BF-BOF, our emission intensity lies in the lower end of the found emission intensities. The reason is that we slightly reduced the consumption of hard coal and coke in our BF-BOF model which is based on European averages (Remus et al. 2013) during the calibration of our model to the German energy statistics (Rohde, 2019). For the novel technology of H2-DRI, different process configurations exist leading to a large range of emission intensities. For EW, studies for a detailed comparison are currently lacking.

Our conclusion that it will be very challenging for the German iron and steel industry to stay within its proportional carbon budget for a 1.5°C climate target is in line with results by studies for the global iron and steel industry (Tong et al., 2019; IEA, 2020b; Wang et al., 2021). Even the strictest scenarios by Wang et al. (2021) exceed the proportional 1.5°C budget by more than 100%.

4.4.3. Implications and recommendations

This study determines different transformation pathways for the German steel industry in line with the Steel Action Concept of the German Federal Ministry for Economic Affairs and Climate Action (BMWK) (BMWi 2020). As suggested by the BMWK, our decarbonization scenarios assume the use of natural gas in direct reduction furnaces (NG-DRI) as an intermediate energy carrier to transition to a 100%-fired hydrogen-based direct reduction (H2-DRI).

Based on this study, we can identify the following challenges and recommendations for the iron and steel industry to meet its sectoral budget.

First, our findings provide further evidence that the emission intensity of the German electricity mix needs to be reduced as fast as possible, such that the minimum emission intensity of indirectly (H2-DRI) or directly (EW, EAF) electrified technologies can be achieved. This is quite challenging for the energy sector especially in the next decade (Simon et al., 2022), due to an expected increase of power demand also in other sectors in the future. According to our findings, for the iron and steel industry alone, additional 81 TWh/year of electricity would be required by 2050. This additional power demand translates into an additional PV capacity of ca. 80 GW, which is ca. 150% of currently installed PV capacity in Germany (53.7 GW (AGEE-Stat, 2021)), or into additional 32 GW of onshore wind turbines (54.4 GW in Germany in 2020 (AGEE-Stat, 2021)). For hydrogen electrolyzers, a capacity of 7.2 GW_{el} would be needed in 2050 (assuming 4545 full-load hours/year (Simon et al., 2022)), which represents an increase by a factor of 360 compared to today (0.02 GW_{el} in 2020 (THEnergy, 2021)) (see section D.6.3).

Secondly, we recommend investments to advance the technology of EW, such that it reaches market maturity earlier than expected, i.e. before 2040. Our findings suggest that EW offers the lowest emission intensity among the technologies considered in this study. Therefore, efforts are needed, such as funding and research capacities, to advance its currently too low TRL. EW seems especially attractive as its specific electricity consumption is roughly one third less than that of H2-DRI (see Figure C-1). Moreover, it does not require a new infrastructure for hydrogen or CCS, but “only” the expansion of capacities for renewable electricity supply.

In contrast, the current lack of a hydrogen infrastructure forms a severe obstacle for a large-scale implementation of H2-DRI. Here, a market revolution would be necessary, similar to what PV experienced during the last decade.

Another obstacle for a large-scale switch to H2-DRI before 2030 is a potentially still large capacity of BF-BOFs ranging from 50% to 100% of current capacities depending on whether relining takes place to extend BF lifetimes (see Figure 3). By 2030, electricity emission factors will ideally have decreased sufficiently to make H2-DRI favorable over BF-BOF. To minimize emissions from these still functional BF-BOFs, one solution could be their early shutdown while simultaneously rapidly switching to H2-DRI. Another solution is the addition of CCS to BF-BOFs.

Our findings suggest that emissions could be minimized the fastest through the implementation of CCS to BF-BOFs as early as possible, e.g. before 2025. First, BF-BOF-CCS may have a lower emission intensity than H2-DRI until 2036-2043 unless electricity is decarbonized sooner than in our optimal assumption (electricity_min). Second, the CCS scenario achieved the lowest cumulative emissions.

This study highlights the need to open the discussion on CCS in Germany, where CCS is currently strongly limited to research purposes and a maximum of 4 Mt CO_2 stored/year within Germany (Federal Ministry of Justice, 2012). The results of this study revealed some points in favor of implementing CCS for BF-BOFs soon: i) the market entry and diffusion rates of H2-DRI and EW alongside the carbon budgets are uncertain and modelled with rather optimistic assumptions in our scenarios; ii) life time extensions of BF-BOFs could limit market entry and thus emission reductions through H2-DRI and EW (see reference scenario); iii) CCS or alternatively negative emission technologies could tackle reaction-related emissions from EAFs to achieve net-zero emissions by 2050 (see Figure 5), which may be about 3.6 Mt CO_2 in 2050, i.e. up to 42% of emissions in 2050. Furthermore, recent research shows that CCS is likely to be required for reaching net-zero emissions in Germany by 2050, e.g. for unavoidable reaction-related emissions from cement production, given the limited capacities of natural sinks (Mengis et al., 2022). Moreover, Germany's Climate Protection Plan mentions CCS as an option to reduce unavoidable emissions in industry (BMU, 2016). Yet, this study can merely show emission reduction potentials of CCS for the steel industry, which is only one of many diverse aspects concerning CCS. Thus, more detailed analyses are required to gain more insights into technical, social, and legal feasibility of CCS, as well as into risk assessments and comparisons to CCU.

Furthermore, future emission reductions in the decarbonization scenarios rely substantially on the increasing market share of scrap-EAF, which almost doubles from 30% in 2020 to up to 57% by 2050 (see Figure 3). Thus, next to decarbonizing primary production, it is crucial to continuously extend capacities of scrap-EAFs in the future (see section C.5 for details), such that the scrap which will be becoming increasingly available can actually be processed and replace primary production.

Lastly, this study emphasizes the necessity to internationally agree on national and ideally also sectoral carbon budgets to accelerate the definition of concrete decarbonization strategies. Despite the uncertainty about the carbon budget for Germany (see Table 5), our results can clearly demonstrate that the German steel sector is likely to exceed its proportional carbon budget by 2037 or even much earlier, unless very drastic measures are taken. As it is a race against time and early measures are needed, we would like to stress again that the cumulative emissions are strongly influenced by the technology pathway (see Figure 6), even though different pathways may lead to very similar emission reductions by 2050, i.e. up to 83% in this study (see Figure 5). Thus, to bring about early as well as effective action, a national strategy is required which outlines a concrete technology pathway for iron and steel producers in Germany. This should be developed considering infrastructure requirements, e.g. for hydrogen, CCU or CCS, and in dialogue with not only research, but also industry and other stakeholders.

4.4.4. Limitations and future research

There are some limitations associated with this study, which could be improved by future research. First, technologies are modelled based on data available from literature due to our primary focus on pathways of future technology mixes instead of an in-depth analysis of each steel production route. Thus, details of individual technologies could be improved in our model, e.g. with primary data from industry. For H2-DRI, future research could try to reduce the uncertainty about its future process configurations and thus its emission-intensity (see Figure D-1). Moreover, the role of hydrogen electrolyzers within future energy systems could be explored. For EW, we could not include the production and consumption of the required alkaline solution due to a lack of reliable data given the novelty of EW. As this process can be energy-intensive (Siderwin, 2021), further research about its effect on the technology's performance is required to avoid problem-shifting.

Secondly, while our study investigated three different scenarios, other future developments are possible. Further research could explore more scenarios and include additional technologies, e.g. high-temperature electrowinning, or scale-up effects of novel technologies (Santos et al., 2016). Moreover, we assumed that the overall demand for steel will stay roughly unchanged, which is in line with other studies (Brunke and Blesl, 2014; Lechtenböhmer et al., 2016; Prognos et al., 2020). Thereby, we addressed the supply side to reduce emissions. To get a full picture, additional research for other potential developments, such as a reduced demand or the influence of a circular economy, is required.

Thirdly, we focused on the switch to primarily electricity-based technologies for primary steel production, since this is key to minimize emissions (Arens et al., 2017; de Coninck et al., 2018). Thus, we did not investigate the application of biomass or syngas to replace residual coal and natural gas requirements in conventional processes, such as the EAF or pellet production, to reach net-zero emissions. Both options might help to further reduce CO_2 emission (Otto et al., 2017), but are alone insufficient for deep emission reductions. Further work could investigate the suitability and implications of such alternative energy carriers alongside the avoidance of reaction-related emissions to achieve net-zero emissions.

This study presents what-if scenarios in which we assume deployment of low-carbon technologies at the scale required for German steel production and calculate the CO_2 emissions on that basis. Analyzing if such scaling up is feasible, and if yes under which economic, political or social conditions, is out of the scope of this paper. Costs play a decisive role in the steel industry, which is internationally highly price-competitive. It has been roughly estimated that a transformation to a low-carbon primary steel production in Germany would require investments of around €30 billion (i.e. €1000/t primary steel production capacity) (BMWi, 2020). Thus, requests for regulations have been voiced to create a level global playing field. Policies under discussion by other studies (Bataille et al., 2018; Wyns et al., 2019; Agora Energiewende & Wuppertal Institut, 2019; BMWi, 2020; IEA, 2020a; Koasidis et al., 2020; Muslemani et al., 2021) are for example: carbon contracts for difference, carbon border adjustments, a labelling scheme for low-carbon steel products, financing of CCS infrastructure, or green public procurement. Moreover, Germany commissioned a study (IEA, 2022) to determine effective policies and economic measures to facilitate the creation of international markets for green steel. Further research is necessary to develop comprehensive national and international policy frameworks taking a systems perspective (Bataille, 2020; Bataille et al., 2021; Nilsson et al., 2021), to investigate societal acceptance, the behavior of individual actors (e.g. using agent-based modelling), or to optimize the operation of the steel industry within the context of larger economic systems.

Lastly, this study assessed *direct* CO_2 emissions of major steel production processes (see Figure 1) and of electricity supply. Emissions occurring across the entire supply chains required to produce steel could be evaluated via the methodology of life cycle assessment (LCA). LCA also allows to evaluate impacts other than greenhouse gases, such as human toxicity or metal depletion. It can thereby reveal whether decarbonization measures may cause negative side-effects in other impact categories, as it has been found for BF-BOF-CCS technologies by Chisalita et al. (2019). Moreover, LCA can help to identify effects of changes in one sector on the environmental performance of other downstream sectors, such as electric vehicles (Koroma et al., 2020; Harpprecht et al., 2021) or the building sector (Zhong et al., 2021).

It is important to note that this study does not aim at offering predictions for the future but analyzes explorative, so-called what-if scenarios. This means that the scenarios are subject to unforeseeable events, such as the Ukraine war and its consequences for the natural gas supply in Germany. On the one hand, the recent steep increase of prices for natural gas in Germany may hamper investments into DRI capacities, which are planned to be firstly run on natural gas, and may thereby delay the transition to H2-DRI (Hermwille et al., 2022). On the other hand, they may incentivize a faster build-up of green hydrogen generation capacities and distribution networks (Hermwille et al., 2022). Future work is required to determine decarbonization scenarios for heavy industry under such very recent, highly uncertain and rapidly changing geopolitical conditions.

As this study openly publishes data and code in a repository (Harpprecht et al., 2022), it provides a basis for future research, e.g. to investigate additional technologies or scenarios. The model and analysis could also be applied to other countries. For this, the following country-specific data inputs would need to be adapted: a) current and future production amounts per technology; b) emission factors of energy carriers, especially of electricity; c) the sectoral carbon budget; and d) the assumptions of the production model may need to be slightly adjusted, as it uses technology data from German and European data sources.

4.5. Conclusions

This study successfully assessed the compatibility of various decarbonization pathways for the German iron and steel industry with a carbon budget. We quantitatively demonstrated that it will be a race against time, since each of our decarbonization scenarios, which we considered already rather optimistic, would exceed the sectoral 1.5°C carbon budgets already in the 2030s.

While we cannot offer a silver bullet to solve the problem, we can conclude that a whole portfolio of measures and technologies will be required to sufficiently limit future CO_2 emissions from iron and steel production in Germany. These comprise a rapid decarbonization of the electricity mix, the construction of a hydrogen infrastructure, the implementation of CCS with a respective infrastructure, early shutdowns of BF-BOFs, and investments to accelerate both maturing processes and final deployment of low-carbon technologies, such as H2-DRI and EW. Ultimately, the question of the ideal technology mix for steel production is not only about CO_2 emissions, but concerns also aspects such as infrastructure requirements for electricity and hydrogen supply, environmental impacts, stakeholders, societal acceptance, regulatory conditions and costs. Future research could investigate these additional aspects, e.g. using life cycle assessment, agent-based modelling or cost optimization.

References

AGEE-Stat. (2021). *Time series for the development of renewable energy sources in Germany*. https://www.erneuerbare-energien.de/EE/Navigation/DE/Service/Erneuerbare_Energien_in_Zahlen/Zeitreihen/zeitreihen.html

Agora Energiewende, & AFRY Management Consulting. (2021). *No-regret hydrogen: Charting early steps for H_2 infrastructure in Europe.* Agora Energiewende.

Agora Energiewende, & Wuppertal Institut. (2019). *Klimaneutrale Industrie: Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement.* Agora Energiewende, Berlin.

Arens, M., Worrell, E., Eichhammer, W., Hasanbeigi, A., & Zhang, Q. (2017). Pathways to a low-carbon iron and steel industry in the medium-term – the case of Germany. *Journal of Cleaner Production*, *163*, 84-98. https://doi.org/10.1016/j.jclepro.2015.12.097

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L. J., Fischedick, M., Lechtenböhmer, S., Solano-Rodriquez, B., Denis-Ryan, A., Stiebert, S., Waisman, H., Sartor, O., & Rahbar, S. (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. *Journal of Cleaner Production*, *187*, 960-973. https://doi.org/10.1016/j.jclepro.2018.03.107

Bataille, C., Nilsson, L. J., & Jotzo, F. (2021). Industry in a net-zero emissions world: New mitigation pathways, new supply chains, modelling needs and policy implications. *Energy and Climate Change*, *2*, 100059. https://doi.org/https://doi.org/10.1016/j.egycc.2021.100059

Bataille, C. G. F. (2020). Physical and policy pathways to net-zero emissions industry. *WIREs Clim Change*, *11*(2), e633. https://doi.org/https://doi.org/10.1002/wcc.633

Bhaskar, A., Assadi, M., & Nikpey Somehsaraei, H. (2020). Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen. *Energies*, *13*(3). https://doi.org/10.3390/en13030758

BMU, 2016. *Klimaschutzplan 2050 Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung.* In: Federal Ministry for the Environment, Nature Conservation, Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit), Berlin, Germany. www.bmuv.de (Accessed 19 September 2022).

BMWi, 2020. *For a strong steel industry in Germany and Europe! The steel action Concept*. BMWi (Bundesministerium für Wirtschaft und Klimaschutz) (Federal Ministry for Economics Affairs and Climate Action). Retrieved from. https://www.bmwi.de/Redaktion/EN/Publikationen/Wirtschaft/the-steel-action-concept.html. (Accessed 18 September 2020).

Brown, T., Gambhir, A., Florin, N., & Fennell, P. (2012). Reducing CO_2 emissions from heavy industry: a review of technologies and considerations for policy makers.

Brunke, J.-C., & Blesl, M. (2014). A plant-specific bottom-up approach for assessing the cost-effective energy conservation potential and its ability to compensate rising energy-related costs in the German iron and steel industry. *Energy Policy*, *67*, 431-446. https://doi.org/https://doi.org/10.1016/j.enpol.2013.12.024

Chisalita, D.-A., Petrescu, L., Cobden, P., van Dijk, H. A. J., Cormos, A.-M., & Cormos, C.-C. (2019). Assessing the environmental impact of an integrated steel mill with post-combustion CO_2 capture and storage using the LCA methodology. *Journal of Cleaner Production*, *211*, 1015-1025. https://doi.org/10.1016/j.jclepro.2018.11.256

Climate Leaders. (2003). *Direct Emissions from Iron and steel production.* United States Environmental Protection Agency (Accessed 20 April 2021).

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., Benson, S. M., Bradley, T., Brouwer, J., Chiang, Y. M., Clack, C. T. M., Cohen, A., Doig, S., Edmonds, J., Fennell, P., Field, C. B., Hannegan, B., Hodge, B. M., Hoffert, M. I., . . . Caldeira, K. (2018). Net-zero emissions energy systems. *Science*, *360*(6396). https://doi.org/10.1126/science.aas9793

de Beer, J., Harnisch, J., & Kerssemeeckers, M. (2000). *Greenhouse gas emissions from major industrial sources - III Iron and steel production*. I. GHG.

de Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A., Dong, W., Ford, J., Fuss, S., Hourcade, J.-C., Mechler, R., Newman, P., Revokatova, A., Schultz, S., Steg, L., & Sugiyama, T. (2018). Strengthening and implementing the global response. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission path-ways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. IPCC-The Intergov-ernmental Panel on Climate Change.

Elshkaki, A., Graedel, T. E., Ciacci, L., & Reck, B. K. (2018). Resource Demand Scenarios for the Major Metals. *Environmental Science and Technology*, *52*(5), 2491-2497. https://doi.org/10.1021/acs.est.7b05154

Federal Ministry of Justice, 2012. Gesetz zur Demonstration der dauerhaften Speicherung von Kohlendioxid (KSpG). (Bundesministerium der Justiz). http://www.gesetze-im-internet.de/kspg/BJNR172610012.html#BJNR172610012BJNG000100000 (Accessed 10 February 2022).

Fischedick, M., Marzinkowski, J., Winzer, P., & Weigel, M. (2014). Techno-economic eval-uation of innovative steel production technologies. *Journal of Cleaner Production*, *84*, 563-580. https://doi.org/https://doi.org/10.1016/j.jclepro.2014.05.063

Gignac, R., & Matthews, H. D. (2015). Allocating a 2 °C cumulative carbon budget to coun-tries. *Environmental Research Letters*, *10*(7). https://doi.org/10.1088/1748-9326/10/7/075004

Hall, B., & Khan, B. (2002). Adoption of new technology. In *New economy handbook*.

Harpprecht, C., Naegler, T., Steubing, B., Tukker, A., & Simon, S. (2022). *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.* v.1.0.1. Zenodo. https://doi.org/10.5281/zenodo.7305509

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

Hasanbeigi, A., Arens, M., & Price, L. (2014). Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction: A technical review. *Renewable and Sustainable Energy Reviews*, *33*, 645-658. https://doi.org/10.1016/j.rser.2014.02.031

Hermwille, L., Lechtenböhmer, S., Åhman, M., van Asselt, H., Bataille, C., Kronshage, S., ... & Trollip, H. (2022). A climate club to decarbonize the global steel industry. *Nature Climate Change*, *12*(6), 494-496. https://doi.org/10.1038/s41558-022-01383-9

Hills, T., Leeson, D., Florin, N., Fennell, P. (2016). Carbon capture in the cement industry: technologies, progress, and retrofitting. *Environmental Science & Technology*, *50*(1), 368-377. https://doi.org/https://doi.org/10.1021/acs.est.5b03508

IEA. (2020a). *Energy Technology Perspectives*. International Energy Agency.

IEA. (2020b). *Iron and Steel Technology Roadmap. Towards more sustainable steelmaking*. International Energy Agency.

IEA, 2022. *Achieving Net Zero Heavy Industry Sectors in G7 Members.* International Energy Agency, Paris. https://www.iea.org/reports/achieving-net-zero-heavy-industry-sectors-in-g7-members. (Accessed 19 September 2022).

IEAGHG. (2013). Iron and Steel CCS Study (Techno-economics Integrated Steel Mill). Report 2013/04.

IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

Kirschen, M., Badr, K., & Pfeifer, H. (2011). Influence of direct reduced iron on the energy balance of the electric arc furnace in steel industry. *Energy*, *36*(10), 6146-6155. https://doi.org/10.1016/j.energy.2011.07.050

Koasidis, K., Nikas, A., Neofytou, H., Karamaneas, A., Gambhir, A., Wachsmuth, J., & Doukas, H. (2020). The UK and German Low-Carbon Industry Transitions from a Sectoral Innovation and System Failures Perspective. *Energies*, *13*(19). https://doi.org/10.3390/en13194994

Koroma, M. S., Brown, N., Cardellini, G., & Messagie, M. (2020). Prospective Environmental Impacts of Passenger Cars under Different Energy and Steel Production Scenarios. *Energies*, *13*(23). https://doi.org/10.3390/en13236236

Lavelaine, H. (2019). *ΣIDERWIN project: electrification of primary steel production for direct CO_2 emission avoidance.* METEC 2019.

Lechtenböhmer, S., Nilsson, L. J., Åhman, M., & Schneider, C. (2016). Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand. *Energy*, *115*, 1623-1631. https://doi.org/10.1016/j.energy.2016.07.110

Lord, M. (2018). *Zero Carbon Industry Plan: Electrifying Industry*. B. Z. Emission. https://bze.org.au/wp-content/uploads/2020/12/electrifying-industry-bze-report-2018.pdf

Lösch, O., Jochem, E., Ashley-Belbin, N., & Zesch, G. (2020). *Bewertung der Direktreduktion von Eisenerz mittels Elektrolyse-Wasserstoff*.

Madeddu, S., Ueckerdt, F., Pehl, M., Peterseim, J., Lord, M., Kumar, K. A., Krüger, C., & Luderer, G. (2020). The CO_2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat). *Environmental Research Letters*, *15*(12). https://doi.org/10.1088/1748-9326/abbd02

Matthews, H. D., Tokarska, K. B., Nicholls, Z. R. J., Rogelj, J., Canadell, J. G., Friedlingstein, P., Frölicher, T. L., Forster, P. M., Gillett, N. P., Ilyina, T., Jackson, R. B., Jones, C. D., Koven, C., Knutti, R., MacDougall, A. H., Meinshausen, M., Mengis, N., Séférian, R., & Zickfeld, K. (2020). Opportunities and challenges in using remaining carbon budgets to guide climate policy. *Nature Geoscience*, *13*(12), 769-779. https://doi.org/10.1038/s41561-020-00663-3

Mayer, J., Bachner, G., & Steininger, K. W. (2019). Macroeconomic implications of switching to process-emission-free iron and steel production in Europe. *Journal of Cleaner Production*, *210*, 1517-1533. https://doi.org/10.1016/j.jclepro.2018.11.118

Mengis, N., Kalhori, A., Simon, S., Harpprecht, C., Baetcke, L., Prats, E., Schmidt‐Hattenberger, C., Stevenson, A., Dold, C., El Zohbi, J., Borchers, M., Thrän, D., Korte, K., Gawel, E., Dolch, T., Heß, D., Yeates, C., Thoni, T., Markus, T., . . . Dittmeyer, R. (2022). Net-zero CO_2 Germany ‐ A retrospect from the year 2050. *Earth's Future*. https://doi.org/10.1029/2021ef002324

Mengis, N., Simon, S., Thoni, T., Stevenson, A., Görl, K., Steuri, B., & Oschlies, A. (2021). *Project Briefing #2 Defining the German Carbon Budget*. Helmholtz Initiative Climate Adaptation and Mitigation. https://www.netto-null.org/imperia/md/assets/net_zero/dokumente/2_carbonbudget_2021_10_web.pdf . (Accessed 14 January 2021).

Meyer, A. (2000). *Contraction and Convergence: The Global Solution to Climate Change* Foxhole, Devon: Green Books.

Moya, J. A., & Pardo, N. (2013). The potential for improvements in energy efficiency and CO_2 emissions in the EU27 iron and steel industry under different payback periods. *Journal of Cleaner Production*, *52*, 71-83. https://doi.org/10.1016/j.jclepro.2013.02.028

Muslemani, H., Liang, X., Kaesehage, K., Ascui, F., & Wilson, J. J. J. o. C. P. (2021). Opportunities and challenges for decarbonizing steel production by creating markets for 'green steel'products. *315*, 128127.

Naegler, T., Becker, L., Buchgeister, J., Hauser, W., Hottenroth, H., Junne, T., Lehr, U., Scheel, O., Schmidt-Scheele, R., Simon, S., Sutardhio, C., Tietze, I., Ulrich, P., Viere, T., & Weidlich, A. (2021). Integrated Multidimensional Sustainability Assessment of Energy System Transformation Pathways. *Sustainability*, *13*(9). https://doi.org/10.3390/su13095217

Neumayer, E. (2000). In defence of historical accountability for greenhouse gas emissions. *Ecological Economics*, *33*(2), 185-192. https://doi.org/https://doi.org/10.1016/S0921-8009(00)00135-X

Nilsson, L. J., Bauer, F., Åhman, M., Andersson, F. N. G., Bataille, C., de la Rue du Can, S., Ericsson, K., Hansen, T., Johansson, B., Lechtenböhmer, S., van Sluisveld, M., & Vogl, V. (2021). An industrial policy framework for transforming energy and emissions intensive industries towards zero emissions. *Climate Policy*, *21*(8), 1053-1065. https://doi.org/10.1080/14693062.2021.1957665

Nuss, P., & Eckelman, M. J. (2014). Life cycle assessment of metals: a scientific synthesis. *PloS one*, *9*(7), e101298.

Otto, A., Robinius, M., Grube, T., Schiebahn, S., Praktiknjo, A., & Stolten, D. (2017). Power-to-Steel: Reducing CO_2 through the Integration of Renewable Energy and Hydrogen into the German Steel Industry. *Energies*, *10*(4). https://doi.org/10.3390/en10040451

Philibert, C. (2017). *Renewable Energy for Industry: From Green Energy to Green Materials and Fuels*. IEA. https://www.iea.org/reports/renewable-energy-for-industry

Prognos, Öko-Institut, & Wuppertal-Institut. (2020). *Klimaneutrales Deutschland. Studie im Auftrag von Agora Energiewende, Agora Verkehrswende und Stiftung Klimaneutralität*. https://www.agora-energiewende.de/veroeffentlichungen/klimaneutrales-deutschland/

Purr, K., Lehmann, H., Nuss, P., Adlunger, K., Balzer, F., Berger, J., Bernicke, M., Bertram, A., Dettling, F., & Drosihn, D. (2019). *Wege in eine ressourcenschonende Treibhausgasneutralität: RESCUE-Studie*. Umweltbundesamt. https://www.umweltbundesamt.de/rescue

Raupach, M. R., Davis, S. J., Peters, G. P., Andrew, R. M., Canadell, J. G., Ciais, P., Friedlingstein, P., Jotzo, F., van Vuuren, D. P., & Le Quéré, C. (2014). Sharing a quota on cumulative carbon emissions. *Nature Climate Change*, *4*(10), 873-879. https://doi.org/10.1038/nclimate2384

Remus, R., Aguado-Monsonet, M. A., Roudier, S., & Sancho, L. D. (2013). *Best Available Techniques (BAT) reference document for iron and steel production: Industrial emissions directive 2010/75/EU: integrated pollution prevention and control (No. JRC69967)*.

Robinius, M., Markewitz, P., Lopion, P., Kullmann, F., Heuser, P., Syranidis, K., Cerniauskas, S., Schöb, T., Reuß, M., & Ryberg, S. (2020). *Wege für die Energiewende: kosteneffiziente und klimagerechte Transformationsstrategien für das deutsche Energiesystem bis zum Jahr 2050*. Forschungszentrum Jülich GmbH.

Robiou du Pont, Y., & Meinshausen, M. (2018). Warming assessment of the bottom-up Paris Agreement emissions pledges. *Nature communications*, *9*(1), 1-10.

Rohde, C., 2019. *Erstellung von Anwendungsbilanzen für die Jahre 2018 bis 2020 für die Sektoren Industrie und GHD. Studie für die Arbeitsgemeinschaft Energiebilanzen e. V. (AGEB) - Entwurf.* Fraunhofer ISI, Karlsruhe.

Ruhwedel, S. (2020). SALCOS, WindH2, GrInHy – Wasserstoffprojekte bei der Salzgitter AG. 4. https://h2-news.eu/forschung/special-wasserstoffprojekte-bei-der-salzgitter-ag/

Ryan, N. A., Miller, S. A., Skerlos, S. J., & Cooper, D. R. (2020). Reducing CO_2 Emissions from U.S. Steel Consumption by 70% by 2050. *Environ Sci Technol*, *54*(22), 14598-14608. https://doi.org/10.1021/acs.est.0c04321

Santos, S. P., Gomes, J. F., & Bordado, J. C. (2016). Scale-Up Effects of CO_2 Capture by Methyldiethanolamine (MDEA) Solutions in Terms of Loading Capacity. *4*(3), 19. https://www.mdpi.com/2227-7080/4/3/19

Siderwin. (2021). *Σiderwin Webinar 24th November 2021*. https://www.youtube.com/watch?v=W8-UiT5ui6M

Simon, S., Xiao, M., Harpprecht, C., Sasanpour, S., Gardian, H., & Pregger, T. (2022). A Pathway for the German Energy Sector Compatible with a 1.5°C Carbon Budget. *Sustainability*, *14*(2). https://doi.org/https://doi.org/10.3390/su14021025

SRU. (2020). *Für eine entschlossene Umweltpolitik in Deutschland und Europa: Umweltgutachten 2020*. Sachverständigenrat für Umweltfragen, Berlin. https://www.umweltrat.de/SharedDocs/Downloads/DE/01_Umweltgutachten/2016_2020/2020_Umweltgutachten_Entschlossene_Umweltpolitik.html. (Accessed 28 June 2021).

Steubing, B., de Koning, D., Haas, A., & Mutel, C. L. (2020). The Activity Browser — An open source LCA software building on top of the brightway framework. *Software Impacts*, *3*, 100012. https://doi.org/10.1016/j.simpa.2019.100012.

Stott, R. (2012). Contraction and convergence: the best possible solution to the twin problems of climate change and inequity. *BMJ*, *344*, e1765. https://doi.org/10.1136/bmj.e1765

THEnergy, 2021. *Operating hydrogen electrolysers with a capacity of 1 MWel and more.* https://www.th-energy.net/english/platform-hydrogen-applications/flagship-proje cts-generation-electrolyzers/. (Accessed 25 January 2022).

Tian, S., Jiang, J., Zhang, Z., & Manovic, V. (2018). Inherent potential of steelmaking to contribute to decarbonisation targets via industrial carbon capture and storage. *Nature communications*, *9*, 1-8. https://doi.org/10.1038/s41467-018-06886-8

Toktarova, A., Karlsson, I., Rootzén, J., Göransson, L., Odenberger, M., & Johnsson, F. (2020). Pathways for Low-Carbon Transition of the Steel Industry—A Swedish Case Study. *Energies*, *13*(15). https://doi.org/10.3390/en13153840

Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., & Davis, S.J.J.N., (2019). Committed Emissions from Existing Energy Infrastructure Jeopardize 1.5°C Climate Target. *Nature, 572*, 373–377. https://doi.org/10.1038/s41586-019-13 64-3.

Umweltbundesamt. (2020). *Carbon Dioxide Emissions for the German Atmospheric Emission Reporting 1990-2018 (in German)*. Federal Environment Agency, Germany. https://www.umweltbundesamt.de. (Accessed 28 October 2020).

UNFCCC. (2021). Greenhouse Gas Inventory Data - Detailed data by Party. https://di.unfccc.int/detailed_data_by_party. UNFCCC.

van Ruijven, B. J., van Vuuren, D. P., Boskaljon, W., Neelis, M. L., Saygin, D., & Patel, M. K. (2016). Long-term model-based projections of energy use and CO_2 emissions from the global steel and cement industries. *Resources, Conservation and Recycling*, *112*, 15-36. https://doi.org/10.1016/j.resconrec.2016.04.016

Vogl, V., Åhman, M., & Nilsson, L. J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production*, *203*, 736-745. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.08.279

Wang, P., Ryberg, M., Yang, Y., Feng, K., Kara, S., Hauschild, M., & Chen, W. Q. (2021). Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. *Nat Commun*, *12*(1), 2066. https://doi.org/10.1038/s41467-021-22245-6

Weigel, M., Fischedick, M., Marzinkowski, J., & Winzer, P. (2016). Multicriteria analysis of primary steelmaking technologies. *Journal of Cleaner Production*, *112*, 1064-1076. https://doi.org/10.1016/j.jclepro.2015.07.132

Worrell, E., Price, L., Neelis, M., Galitsky, C., & Zhou, N. (2007). *World best practice energy intensity values for selected industrial sectors*. https://escholarship.org/uc/item/77n9d4sp

WSA. (2019a). *Steel statistical yearbook 2019 concise version*. World Steel Association. https://www.worldsteel.org/en/dam/jcr:7aa2a95d-448d-4c56-b62b-b2457f067cd9/SSY19%2520concise%2520version.pdf

WSA. (2019b). *World steel in figures 2019*. World Steel Association. https://worldsteel.org/wp-content/uploads/2019-World-Steel-in-Figures.pdf. (Accessed 13 July 2021).

WSA. (2020). *Steel Statistical Yearbook 2020 concise version*. World Steel Association. https://worldsteel.org/wp-content/uploads/Steel-Statistical-Yearbook-2020-concise-version.pdf. (Accessed 9 November 2021).

Wuppertal Institut. (2020). *CO_2-neutral bis 2035: Eckpunkte eines deutschen Beitrags zur Einhaltung der 1,5°C-Grenze*. Wuppertal Institut für Klima, Umwelt, Energie, Wuppertal. https://nbn-resolving.org/urn:nbn:de:bsz:wup4-opus-76065.

WV-Stahl. (2019). *Fakten zur Stahlindustrie in Deutschland 2019.* WV Stahl: Wirtschaftsvereinigung Stahl (German Steel Federation). https://issuu.com/stahlonline/docs/wvstahl_fakten_zur_stahlindustrie_2019.

Wyns, T. G., Khandekar, G. A., Axelson, M., Sartor, O., & Neuhoff, K. (2019). *Industrial Transformation 2050-Towards an Industrial strategy for a Climate Neutral Europe, IES. Available at ies.be*

Yuan, B., Kongstein, O. E., & Haarberg, G. M. (2009). Electrowinning of iron in aqueous alkaline solution using a rotating cathode. *Journal of The Electrochemical Society*, *156*(2), D64.

Zhang, X., Jiao, K., Zhang, J., & Guo, Z. (2021). A review on low carbon emissions projects of steel industry in the World. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2021.127259

Zhong, X., Hu, M., Deetman, S., Steubing, B., Lin, H. X., Hernandez, G. A., Harpprecht, C., Zhang, C., Tukker, A., & Behrens, P. (2021). Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060. *Nature* *communications*, *12*(1), 1-10. https://doi.org/https://doi.org/10.1038/s41467-021-26212-z.

5 Future environmental impacts of global iron and steel production

This chapter has been published as:
Harpprecht, C., Sacchi, R., Naegler, T., van Sluisveld, M., Daioglou, V., Tukker, A., & Steubing, B. R. (2025). Future Environmental Impacts of Global Iron and Steel Production. *Energy & Environmental Science*. https://doi.org/10.1039/D5EE01356A

The electronic supplementary information (ESI) is available at:
https://www.rsc.org/suppdata/d5/ee/d5ee01356a/d5ee01356a1.pdf

Abstract

The iron and steel industry is not only responsible for up to 9% of global greenhouse (GHG) emissions, but also associated with other environmental impacts. Anticipated growth in steel demand thus poses significant challenges to climate and environmental objectives. This study evaluates the future life cycle environmental impacts of global steel production, accounting for the adoption of emerging production technologies, including carbon capture and storage (CCS), hydrogen-based or electrified processes. We couple state-of-the-art life cycle assessment (LCA) models of current and future steel production routes with multi-sectoral, internally consistent scenarios for future energy and steel supply from the integrated assessment model (IAM) of IMAGE. This approach provides a comprehensive assessment of regional and temporal environmental impacts for three climate mitigation pathways: a 3.5°C baseline, a <2°C- and a 1.5°C-target. Results demonstrate 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 used. They thereby clearly outperform CCS technologies for coke-based processes. Nevertheless, it is unlikely that global steel production will reach net-zero GHG emissions by 2060, with its emission intensity decreasing by -33% (3.5°C-baseline), -56% (<2°C-target), and -79% (1.5°C-target) compared to 2020. Considering future steel demand growth, global annual GHG emissions may only be reduced by up to -67% by 2060, from 3.4 in 2020 to 1.2 Gt CO_2-eq./year. Cumulative emissions from steel production could thus consume 18-30% of the global end-of-the-century 1.5°C carbon budget and 9-14% of the 2°C budget by 2060. Our analysis reveals that the decarbonization scenarios could shift burdens from climate change to other impact categories, such as ionising radiation, land use, or material resources. The drivers of rising impacts are diverse and caused by different processes, e.g., electricity generation, furnace slag treatment, metal mining, or chemical production. Achieving sustainable steel production requires not only rapid decarbonization and demand reduction but also targeted process-specific interventions throughout the entire life cycle to mitigate future environmental impacts.

5.1. Introduction

The iron and steel industry is responsible for about 9% of global GHG emissions due to its high energy intensity and current dependence on fossil fuels (P. Wang et al., 2021). Being a key building material for infrastructure and technologies, steel ranks third in most produced materials globally, following cement and timber (IEA, 2020). Steel demand is expected to increase further (P. Wang et al., 2021; Yokoi et al., 2022), potentially up to 86% by 2050 (Watari et al., 2021). This poses significant challenges to climate and environmental goals (Tong et al., 2019; P. Wang et al., 2021; Watari et al., 2023), since steel production causes environmental pressures not only for GHG emissions but also for various indicators, such as human toxicity (e.g., due to chromium emissions in landfilled slags) (Schenker et al., 2022) or particulate matter emissions (e.g., from blast furnaces, coke ovens or sinter plants) (IRP, 2019; Nuss & Eckelman, 2014; Remus et al., 2013).

Addressing demand growth solely through energy efficiency improvements is insufficient to curb the steel sector's global emissions (van der Voet et al., 2019; P. Wang et al., 2021). Hence, substantial emission cuts may only be achieved by reducing demand or adopting novel technologies, such as electrified production technologies (van der Voet et al., 2019; P. Wang et al., 2021; Yokoi et al., 2022), while simultaneously decarbonizing upstream processes for material and energy supply, such as electricity and hydrogen supply.

Technologies considered promising are direct reduction of iron (DRI), which can be operated either with natural gas (NG), or hydrogen (H2) (Zhang et al., 2021). Although NG-DRI is already a mature technology with a lower emission intensity than the conventional coke-based blast furnace (BF), it is currently not widely adopted because natural gas is in most regions not economically competitive with coke (Moya & Pardo, 2013). As an alternative to natural gas, direct reduction can also be operated with hydrogen (H2-DRI) (Beer et al., 2000), which can offer even greater CO_2 emission reduction depending on the emission intensity of hydrogen generation (Bhaskar et al., 2020; Fischedick et al., 2014). Another emerging but less mature technology is the electrolysis of iron ore, which uses electricity to reduce iron, thus enabling direct electrification. Specifically, electrowinning (EW) allows iron production at low temperatures (110°C) (EC, 2016; Lavelaine, 2019; Yuan et al., 2009). To reduce direct emissions of iron production, carbon capture and storage (CCS) technologies can be deployed and potentially retrofitted to existing furnaces, e.g., BFs.

Current assessments often prioritise direct GHG emissions of the steel industry at national[1] or global scales (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), yet frequently neglect indirect emissions or broader environmental impacts.

Some studies adopt a life cycle approach to assess emissions from emerging low-carbon technologies like hydrogen-based direct reduction of iron (H2-DRI) (Koroma et al., 2020; Li et al., 2022), carbon capture and storage (CCS) (Chisalita et al., 2019), or electricity-based electrowinning (EW) (Harpprecht, Naegler, Steubing, & Sacchi, 2022). These analyses re-

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

veal potential burden shifting to upstream supply chains or non-climate change impact categories, emphasising the need for comprehensive life cycle assessments (LCAs) to guide investment decisions to a low-impact steel supply chain.

LCA offers a systematic method for evaluating environmental impacts across the entire life cycle of a product enabling stakeholders to identify strategies to minimize emissions based on a systems perspective (ISO, 2006). Prospective LCAs extend this capability by integrating future scenarios to provide insights into the environmental implications of future developments, e.g., emerging technologies or policies (Langkau et al., 2023; van der Giesen et al., 2020). Achieving coherent results requires consistency in scenario assumptions across regions and sectors (Steubing et al., 2023). Such a holistic approach equips decision-makers with the necessary information to align steel industry pathways with global climate and environmental goals.

Previous studies evaluated future life cycle impacts of iron and steel supply in conjunction with global demand scenarios, but used scenario data from disparate sources. Moreover, they primarily assessed climate change impacts (P. Wang et al., 2021; Yokoi et al., 2022). Only one study investigates additional impact categories (van der Voet et al., 2019).

Research has yet to fully explore the environmental implications of global steel supply using multi-sectoral, internally consistent decarbonization scenarios while accounting for a broad range of emerging technologies and non-climate impacts.

Integrated assessment models (IAMs) are promising sources for internally coherent scenario data across multiple sectors (Steubing et al., 2023). IAMs are global energy-economic-environmental models aiming at capturing the interactions between human systems and the implications for 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 socioeconomic narratives (e.g., Shared Socioeconomic Pathways (SSPs)) and emission constraints (e.g., Representative Concentration Pathways (RCPs)) (O'Neill et al., 2014).

While prior work has coupled IAM scenarios and LCA, studies mostly focused on the electricity (Cox et al., 2018; Mendoza Beltran et al., 2018; Sacchi et al., 2021), and recently, the cement sector (Müller et al., 2024). Specific climate change impacts of the global steel market have been assessed using scenarios from IAMs (Sacchi et al., 2021), e.g., IMAGE (Stehfest et al., 2014), but the assessment did not include novel technologies, such as H2-DRI or EW. Another analysis investigated future climate change impacts of a single German steel mill (Weckenborg et al., 2024) using background energy scenarios from the IAM REMIND (Baumstark et al., 2021).

In this study, we couple state-of-the-art LCA models of current and future steel production routes with multi-sectoral, internally consistent scenarios for future energy and steel supply, as the scenarios have been modelled by one IAM, i.e., IMAGE. We obtain a comprehensive and supply chain-based overview of the environmental impacts of steel production across different world regions over time. This approach allows us to investigate the following research questions:

1. *What are the future environmental impacts of global steel production under consistent energy and steel supply scenarios?*
2. *Could a decarbonization of steel production cause adverse side effects in impact categories other than climate change?*
3. *Can global climate change and other environmental impacts of steel production be reduced despite growing demand, such that a decoupling may be achieved?*

5.2. Methods

5.2.1. Goal and scope

This study aims to assess the environmental impacts of future global steel production using coherent multi-sectoral scenarios, i.e., for both steel and energy supply. We conduct a prospective attributional life cycle assessment (LCA) from 2020 to 2060 with a cradle-to-gate scope. The functional units are 1 kg of steel supplied by the average global steel market, and the total supply required to meet future global steel demand (quantities are scenario-specific).

The scenarios are based on the IAM IMAGE[2] (Stehfest et al., 2014) (Figure 1, Section 5.2.2). The IMAGE steel production model includes eight primary and one secondary production route (Figure 2), representing the most common and promising technologies. They are regionalised into 26 world regions (electronic supplementary information (ESI) Section S1.1.3).

We integrate the energy and steel supply scenarios from IMAGE into the life cycle inventory (LCI) database of ecoinvent (v3.9.1 cut-off (Wernet et al., 2016)) using the open-source Python library premise[3] (Sacchi et al., 2021) (Figure 1). For each sectoral scenario, premise imports new LCIs, creates supply chains for 26 world regions, generates new regional supply markets based on production volumes by supply chain (e.g., for future electricity mixes), and finally relinks these new supply chains and markets to downstream consumers within the database. We thereby create futurized versions of the database representing the future system described in the scenarios—an approach referred to as 'background scenario' integration.

All scenario data is sourced from IMAGE for the SSP2 pathway and three climate change mitigation pathways: 3.5°C, <2°C, and 1.5°C (Section 5.2.2), representing the global mean surface temperature increase by 2100, relative to pre-industrial levels. The background scenarios futurize major energy-consuming sectors (electricity, fuels, cement, and transport) in the LCI database and are generated using premise.

The steel production scenarios of IMAGE cover:

- eight primary steel production routes and secondary production (Figure 2): blast-furnace and basic-oxygen furnace (BF-BOF); BF-BOF with top gas recycling (TGR-BF-

[2] IMAGE=Integrated Model to Assess the Global Environment, scenarios are used from version 3.3 (PBL 2024).

[3] Version: 2.1.1.dev4, premise = PRospective EnvironMental Impact asSEssment, see ESI section S1.4.1

BOF); natural gas-based direct reduction (NG-DRI); hydrogen-based direct reduction (H2-DRI); electrowinning (EW); application of carbon capture and storage (CCS) to three routes (BF-BOF-CCS, TGR-BF-BOF-CCS, NG-DRI-CCS); and scrap-based electric arc furnaces (scrap-EAF);

- technology-specific energy efficiency improvements;
- regional production volumes for 26 regions per production route (primary and secondary) are used to create regional steel markets (Figure 4).

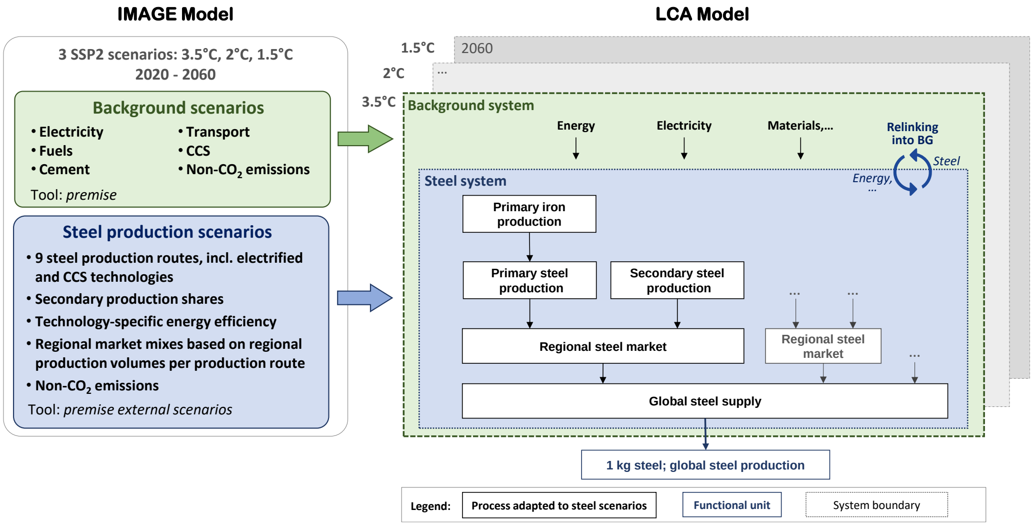


Figure 1: Model coupling and scenario integration of the IMAGE scenarios into the LCA model using premise. More detailed flowcharts for the different steel production routes are provided in Figure 2, Section 5.2.2 explains the IMAGE scenarios. BG: background; CCS: carbon capture and storage; SSP: Shared Socioeconomic Pathways.

5.2.2. Inventory analysis

Life cycle inventories of steel production routes

We developed detailed bottom-up LCIs of each steel production route to translate the IMAGE scenarios into a comprehensive LCA model. Our steel model considers nine steel production routes which supply steel in varying shares to regional steel markets (Figure 2). It includes the main stages of raw material preparation production (e.g., sinter or pellet production), iron production (e.g., via BF, DRI, or EW), and steel production (e.g., via BOF or EAF).

Current steel production (BF-BOF, scrap-EAF): The conventional steel production routes are the coke-based blast-furnace and basic-oxygen furnace (BF-BOF) for primary production and the electric arc furnace (EAF) for secondary production, which is predominantly electricity-operated. Their processes, and all other white boxes in the figure, are primarily based on ecoinvent processes, although they might be slightly modified, e.g., to align models (see Section 5.2.2).

TGR-BF-BOF: A top gas recycling (TGR) unit can be retrofitted to BFs. TGR separates CO_2 from the BF top gas using Vacuum Pressure Swing Adsorption (VPSA) to produce a CO-rich gas for reinjection into the BF as a reducing agent. Thereby, coke and hard coal consumption of the BF can be decreased by 24.5%, reducing direct CO_2 and CO emissions of the BF by 24% and 90%, respectively (Quader et al., 2016). For the VPSA, we assume an adsorbent based on zeolite (0.75 kg/ton pig iron (Choi, 2013)) and an electricity consumption of 83 kWh/ton pig iron (A. Otto et al., 2017).

NG-DRI: For natural gas-based direct reduction (NG-DRI), we assume that iron is produced in a shaft furnace using the Midrex process (Nduagu et al., 2022). The iron is refined to steel via an electric arc furnace (EAF), which is also applied to iron from H2-DRI and EW.

H2-DRI: We assume that hydrogen is sourced from the respective regional markets of hydrogen from IMAGE, which includes efficiency scenarios and scenarios for the generation mix. Thus, hydrogen may not be generated purely from renewables, but, for example, from natural gas too (ESI Section S1.2.5). The LCI for DRI is based on a recent study (Li et al., 2022) and is complemented by the electrical preheating of iron ore pellets and hydrogen (Bhaskar et al., 2020; Hölling & Gellert, 2018). In a sensitivity analysis, we assess green hydrogen for iron production, labelled green H2-DRI. The green hydrogen is sourced from PEM (proton exchange membrane) electrolysers operated with renewable electricity only, i.e., from onshore wind turbines (ESI Section S1.3.3), as hydrogen from electrolysis causes lower GHG emissions than from fossil fuels (Wei et al., 2024).

EW: Iron production can be directly electrified via the novel process of electrolysis of iron ore. This eliminates conversion losses associated with hydrogen generation. Specifically, electrowinning (EW) allows iron production at low temperatures (110°C) using an alkaline electrolyte, e.g., sodium hydroxide (Yuan et al., 2009). We use data from a pilot plant of the SIDERWIN project (EC, 2016; Lavelaine, 2019; Siderwin, 2020) in France. We assume that electricity is sourced from the respective regional markets for electricity.

CCS technologies for BF-BOF-CCS, TGR-BF-BOF-CCS, and NG-DRI-CCS: To reduce direct emissions of the iron production processes of the BF, TGR-BF, and NG-DRI, carbon capture and storage (CCS) facilities can be retrofitted, leading to three additional production routes. BF-BOF-CCS uses mono-ethanolamine (MEA) as CO_2 absorbent (IEAGHG, 2013). The TGR-BF-BOF-CCS and NG-DRI-CCS options apply the zeolite-based VPSA followed by a cryogenic flash and compression process, which increases the purity of the CO_2 gas and makes it suitable for transport (Keys et al., 2019; Quader et al., 2016). The CCS processes require additional energy but also reduce NOx, SO2 and dust emissions during gas pretreatment (ESI Section S1.3) (Choi, 2013; Ho et al., 2008; Voldsund et al., 2019). CO_2 transport and storage are taken from premise based on Volkart et al. (2013) assuming the most conservative transport distance (400 km) and storage depth (3 km).

Further details for the LCIs are provided in the ESI Section S1.3.

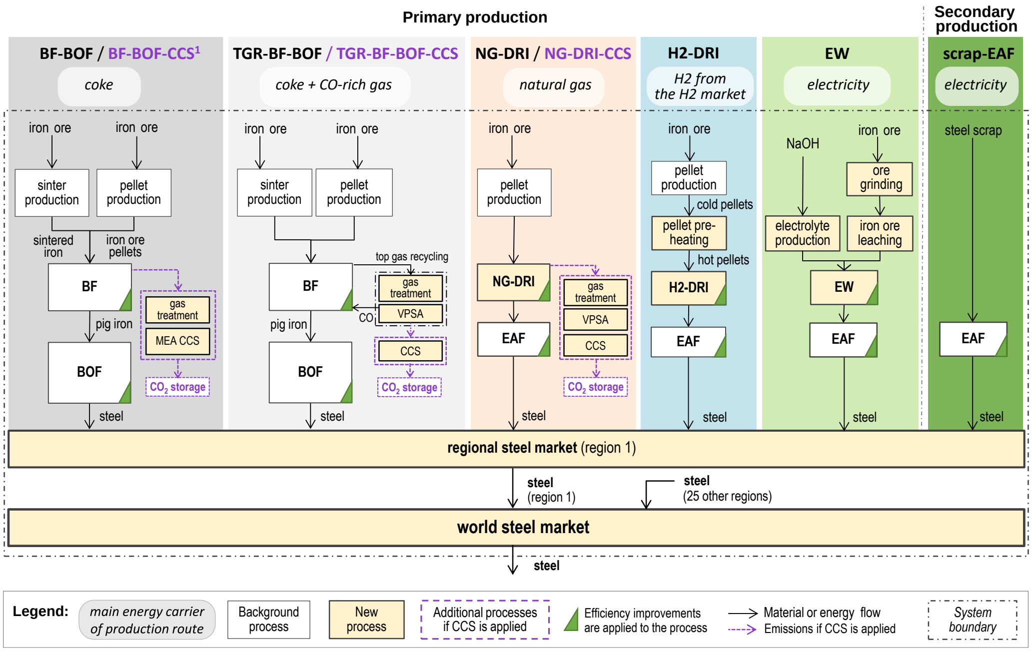


Figure 2: Simplified flowcharts of the steel production model and the creation of regional steel markets. For all processes, incl. the CCS processes, emissions occur but are not depicted due to space restrictions. This example shows a regional market for unalloyed steel. For the other steel markets, see ESI Sections S1.4.2-S1.4.3. More details about each production route are provided in Section S1.3.1: CCS is illustrated here within the respective base technologies (BF-BOF, TGR-BF-BOF, NG-DRI) due to space restrictions, but it represents a respective individual production route. BF-BOF: blast-furnace and basic-oxygen furnace; CCS: carbon capture and storage; CO: carbon monoxide; EW: electrowinning; H2-DRI: hydrogen-based direct reduction; MEA: mono-ethanolamine; NaOH: sodium hydroxide; NG-DRI: natural gas-based direct reduction; scrap-EAF: scrap-based electric arc furnace; TGR-BF-BOF: top gas recycling blast-furnace and basic-oxygen furnace; VPSA: Vacuum Pressure Swing Adsorption.

Global steel production model

We model global steel supply as the sum of regional steel markets based on their respective production volumes in the respective scenario. Each regional market is created for six different steel types.

Steel types: We consider six different steel types using their current global production shares from ecoinvent: unalloyed (82.9%), low-alloyed (3.7%), chromium (1.8%), reinforcing steel (4.5%), hot-rolled low-alloyed (5.3%) and hot-rolled chromium (1.8%) steel (ESI Section S1.4.2). A global market group summarises global steel production from all six steel types (ESI Section S1.4.3). The future regionalised and technology-specific steel production mix is implemented for all steel types apart from chromium steel, which is produced using the EAF.

Alloying elements: Alloying elements are added depending on the steel type based on data from existing ecoinvent processes (ESI Section S1.4.4).

Additional assumptions: Given the different model structures of IMAGE and LCA models, specifically ecoinvent and our steel LCIs, we adapted the LCA models to ensure consistency of assumptions. Primary production routes are purely primary, only using iron-bearing materials from primary sources, excluding scrap, while secondary production is purely secondary, using only scrap as input (Sections S1.4.5, S3.2).

Steel scenarios from IMAGE

Three scenarios from the IAM IMAGE are considered: a Base (3.5°C) scenario, a <2°C, and a 1.5°C scenario. They all use the Shared Socioeconomic Pathway SSP2, also called middle-of-the-road, as economic, demographic and political trends continue without major changes (Riahi et al., 2017) (Figure 3). The Base scenario assumes no specific climate mitigation targets, leading to about 3.5°C warming by 2100. For the <2°C- and 1.5°C scenarios, the SSP is combined with two Representative Concentration Pathways (RCPs), which represent the climate targets and limit the atmospheric radiative forcing by 2100 to 2.6 and 1.9 W/m2, respectively.

IMAGE is a process-based IAM which models physical flows with high sectoral and regional resolution. Its strength lies in a detailed representation of the industrial sector, especially for the steel and cement sectors (Müller et al., 2024; Stehfest et al., 2014; van Ruijven et al., 2016; van Sluisveld et al., 2021). While other IAMs model the industrial sectors based on exogenous assumptions without technology-specific process data, IMAGE distinguishes different production technologies and their respective parameters (Edelenbosch et al., 2017). We updated the steel technology parameters for IMAGE v.3.3 to more recent data regarding specific energy consumption (SEC), floor values, and carbon capture rates (ESI Section S1.1.2).

Steel production capacities are modelled considering current stocks (assuming a lifetime of 30 years) and optimising the costs of new capacities, considering capital and operational expenditures (e.g., for fuel demand and considering efficiency improvements) and context-related costs, such as carbon taxes (ESI Section S1.1.2). Steel demand is based on a stock model for four product categories of variable lifetimes (buildings, machinery, cars and packaging) (van Ruijven et al., 2016), which also determines scrap availability and future secondary steel production shares. More details about IMAGE and the steel submodule are provided in the ESI (Sections S1.1, S1.2) or related literature (Stehfest et al., 2014; van Ruijven et al., 2016; van Sluisveld et al., 2021).

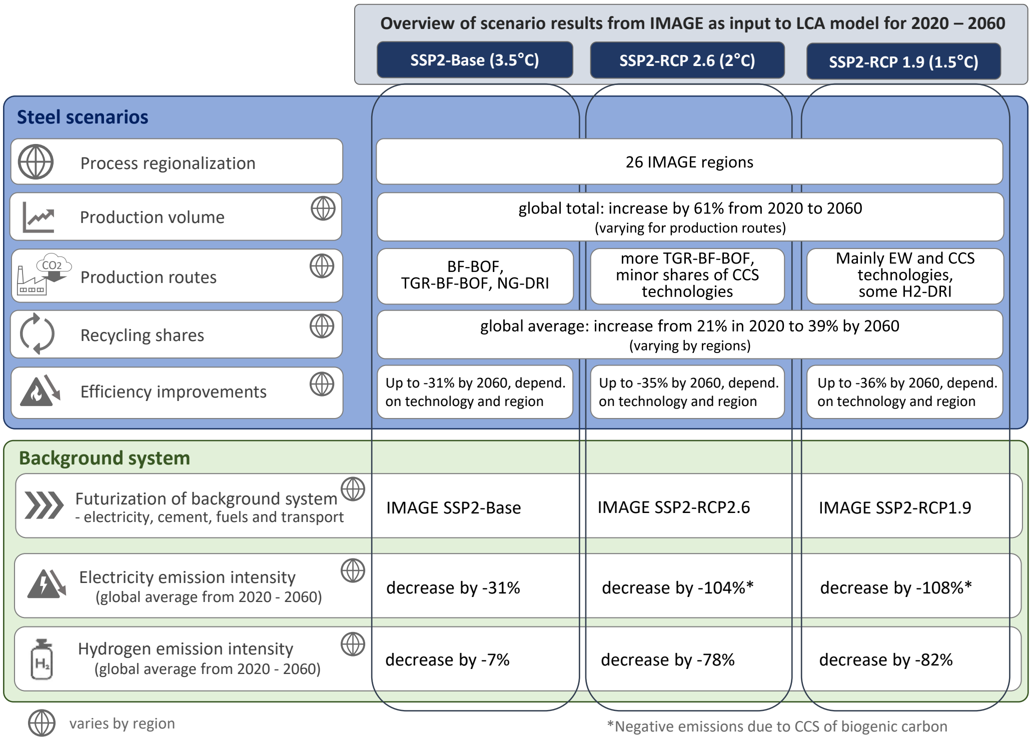


Figure 3: Overview of multi-sectoral scenarios from the integrated assessment model IMAGE for steel and background scenarios. BF-BOF: blast-furnace and basic-oxygen furnace; CCS: carbon capture and storage; EW: electrowinning; H2-DRI: hydrogen-based direct reduction; NG-DRI: natural gas-based direct reduction; RCP: Representative Concentration Pathways; SSP: Shared Socioeconomic Pathways; TGR-BF-BOF: top gas recycling blast-furnace and basic-oxygen furnace.

Future global steel production: For all scenarios, global steel production grows by 61% from 2020 to 2060 (from 1640 to 2634 Mt steel/year) with primary production increasing by 25% (see Figure 4.a, ESI Section S1.2.3). In IMAGE, material production is GDP-driven, which is the same across all scenarios for SSP2.

Regionalization of steel production: Steel production is regionalized distinguishing 26 world regions (ESI Section S1.1.3). While China is the largest producer in 2020, accounting for 55% of the market share, production partly relocates by 2060, e.g., to India (14%) and Eastern Africa (13%) (see Figure 4.a, ESI Section S1.2.2).

Market shares of steel production routes: Secondary production shares (scrap-EAF) increase from 21% to 39% by 2060 (see Figure 4.b, ESI Section S1.2.3). Primary production, however, exhibits a shift towards novel primary production, which intensifies with stronger climate goals. While the coke-based BF-BOF production decreases from 74% in 2020 to 40% and 25% in the 3.5°C and 2°C scenarios by 2060, it gets entirely phased out in the 1.5°C scenario. In the Base scenario, alternatives for primary production are limited to TGR-BF-BOF (13.5%) and DRI-EAF (6.8% in 2060).

In the 2°C scenario, CCS is deployed as a minor technology for BF-BOF-CCS (3.7%), NG-DRI-CCS (7.5%), and TGR-BF-BOF-CCS (1.5%), but it gains relevance in the 1.5°C scenario, with TGR-BF-BOF-CCS supplying 13.3% and NG-DRI-CCS 9.3% by 2060.

The electrified EW becomes a key technology in the 1.5°C scenario representing the majority (29.8%) of primary production. In contrast, H2-DRI plays only a minor role (8.2%) given a too high emission intensity of hydrogen generation.

Smelting reduction furnaces, i.e., SR-BOF and SR-BOF-CCS, are not deployed, given their comparatively high energy requirements and low CCS capture rate (ESI Section S1.1.2). Therefore, they are not further considered in this study.

Efficiency improvements of steel production: We apply technology- and region-specific efficiency improvements to the processes of iron and steel production (see Figure 2, ESI Section S1.2.4). Efficiency improvements are derived from the IMAGE scenarios (see Figure 4.c) but slightly corrected as documented in ESI Section S1.2.4. For instance, they are limited to a maximum of 1.1%/year, i.e., the maximum rate from literature (van Sluisveld et al., 2021), leading to a maximum decrease of specific energy consumption (SEC) of -36% from 2020 to 2060. Efficiency improvements are not applied to iron-bearing materials or alloying elements to ensure the correctness of mass balances (Section S1.2.4).

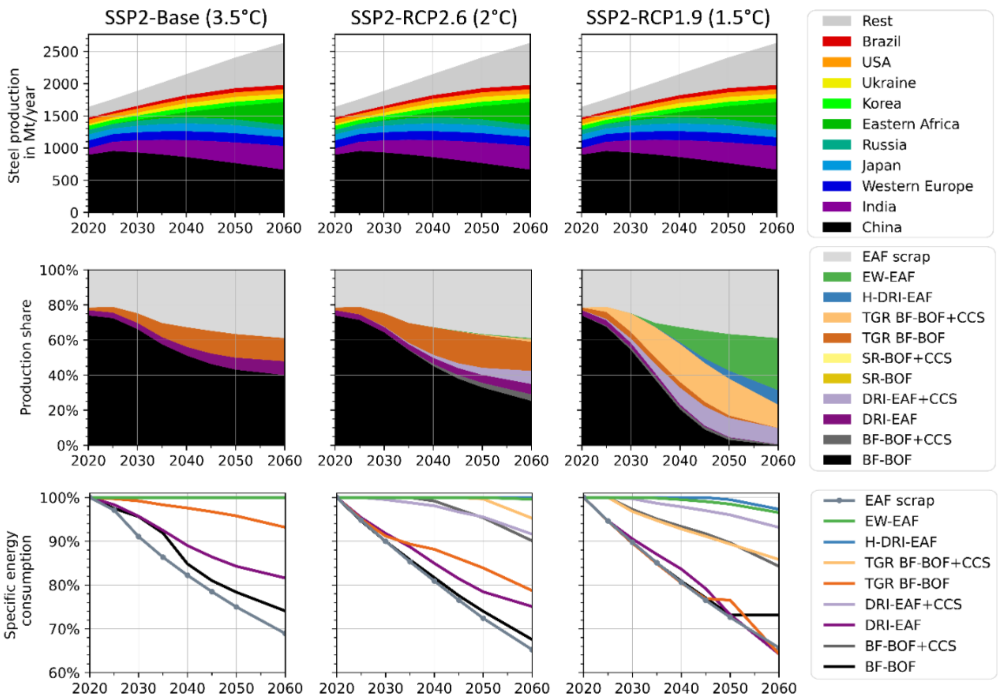


Figure 4: Global steel production scenarios according to the scenarios from IMAGE. Steel production by a) region showing the top ten steel producing regions; and b) by production route. c) Development of specific energy consumption (SEC) for each steel production route relative to the energy consumption in 2020. More detailed figures are provided in the ESI: regional production shares (Section S1.2.2); market mixes of different regions (Section S1.2.3); and SEC for each technology depending on the region (Section S1.2.4). BF-BOF: blast-furnace and basic-oxygen furnace; CCS: carbon capture and storage; EW: electrowinning; H2-DRI: hydrogen-based direct reduction; NG-DRI: natural gas-based direct reduction; RCP: Representative Concentration Pathways; scrap-EAF: scrap-based electric arc furnace; SR-BOF: smelting reduction and basic-oxygen furnace; SSP: Shared Socioeconomic Pathways; TGR-BF-BOF: top gas recycling blast-furnace and basic-oxygen furnace.

5.2.3. Life cycle impact assessment

We use the IPCC 2021 GWP 100a method (IPCC, 2021) to assess climate change impacts. We complement the GWP100a indicator with characterisation factors for hydrogen emissions to air (+11 kg CO_2-eq./kg H2 (Sand et al., 2023)) and non-fossil CO_2 emissions and uptake (+/- 1 kg CO_2-eq./kg CO_2) (ESI Section S1.5), to correctly account for emissions of hydrogen supply and biomass-fuelled CCS technologies (Sacchi et al., 2021). Midpoint indicators from the Environmental Footprint 3.0 method (Fazio et al., 2018) are used for other impact categories.

The LCA results are calculated using the Activity Browser (Steubing et al., 2020) and the superstructure approach (Steubing & Koning, 2021).

5.3. Results

5.3.1. Future climate change impacts of steel production routes

Figure 5 illustrates climate change impacts per kg of steel for the nine production routes in 2060 under the three scenarios compared to 2020.

The net emission intensity (black crosses) of all production routes decreases with more ambitious climate goals, ranging from -46 to -95% by 2060 compared to the BF-BOF in 2020. An exception forms the BF-BOF, whose efficiency stagnates in the 1.5°C scenario. The lowest emission intensity is achieved by the electricity-based technologies of secondary production (scrap-EAF) and EW in 2060, both almost reaching net-zero, i.e., 0.12 kg CO_2-eq./kg of steel. However, this strongly depends on the emission intensity of electricity, which is by far the most prominent contributor (78% for EW in 2020). In some instances, electricity can have a net negative contribution due to biomass use combined with CCS (BECCS, see ESI Section S1.2.5).

For the conventional processes (BF-BOF, TGR-BF-BOF, and NG-DRI), the largest contributors are direct emissions from iron production (red; 33-60%) and iron sinter and pellet production (orange; 3-32%), with smaller contributions from indirect emissions due to the supply of coke and coal (1-13%), electricity (1-33%) and natural gas (1-13%).

The impacts of electrified or novel steelmaking technologies like H2-DRI, EW, and scrap-EAF are primarily driven by indirect emissions from hydrogen, electricity, natural gas, and biomass supply. Thus, in 2020, if operated with the current electricity and hydrogen mix, the emission intensity of EW would be 62% higher and of H2-DRI only 1% lower than that of the BF-BOF. These technologies achieve their maximum emission reductions of -95% and -83%, respectively, only with a decarbonized energy supply under ambitious climate scenarios. This is because, in the IMAGE scenarios, hydrogen production relies mainly on natural gas or natural gas with CCS (see ESI Section S1.2.5), with renewable hydrogen playing a minor role, contributing less than 15% by 2060 in the 1.5°C scenario. This underscores the importance of a systems perspective and explains why H2-DRI and EW are not deployed in the IMAGE 3.5°C scenario (see hatched bars). However, using green hydrogen (via electrolysis powered by wind energy) can drastically lower H2-DRI's emissions by

33%-42%, reducing its intensity from 0.38 to 0.25 kg CO_2-eq./kg steel by 2060 (green crosses in Figure 5).

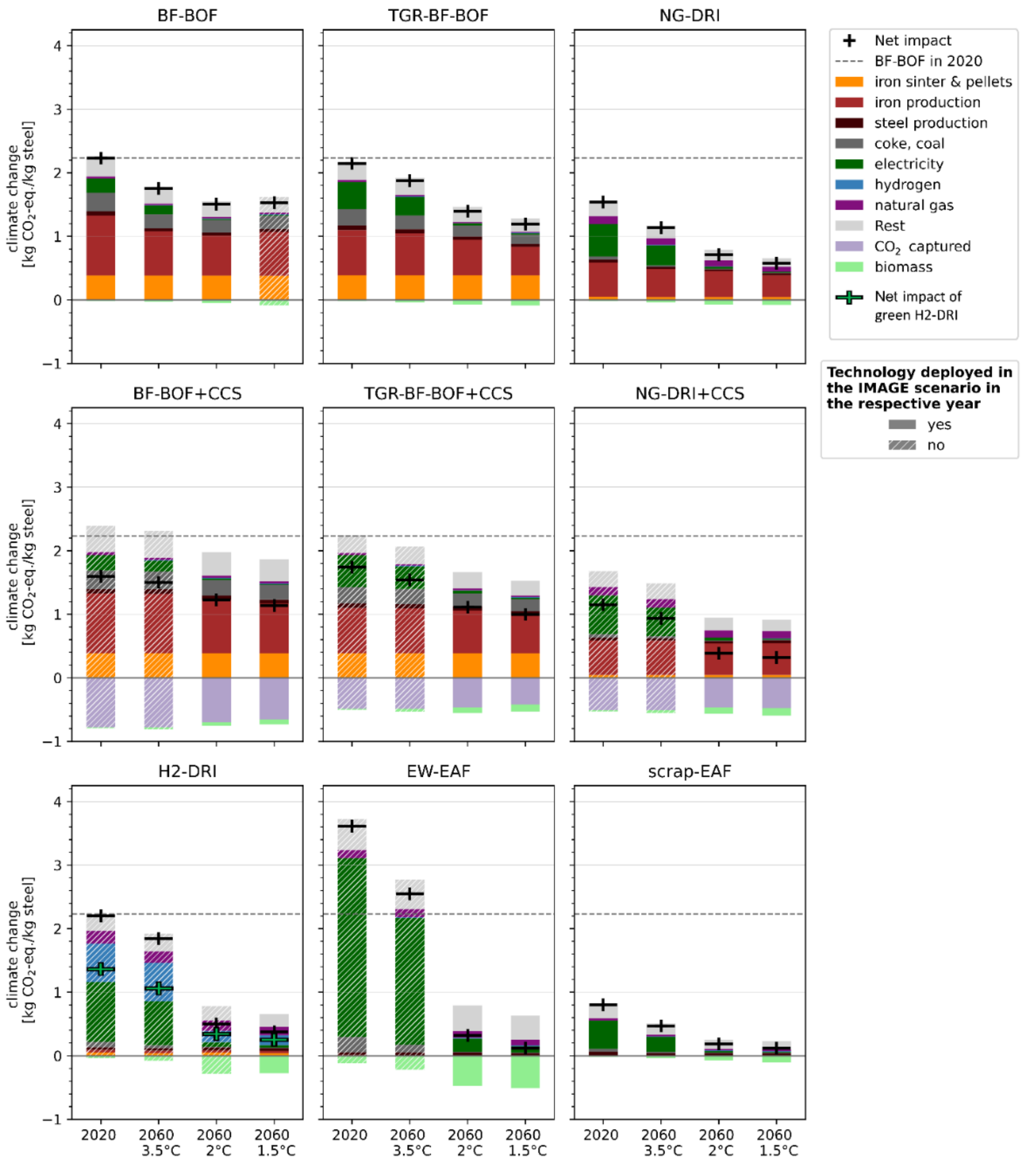


Figure 5: Climate change impacts for nine steel production routes per kg steel in 2060 compared to 2020 under different climate goal scenarios. The hatching indicates that the technology is not part of the steel production mix in that specific scenario and scenario year of the IMAGE scenarios. H2-DRI: Green crosses denote net impact of green H2-DRI compared to H2-DRI which sources hydrogen from the average hydrogen mix (black crosses). Functional units: world datasets for unalloyed steel, apart from scrap-EAF, which is low-alloyed steel; scenarios: SSP2; premise: all sectors updated; contribution cut-off at 0.1%, contributors are aggregated by reference product and were partly manually grouped. Biomass: biogenic CO_2, i.e., CO_2 uptake during biomass growth; BF-BOF: blast-furnace and basic-oxygen furnace; CCS: carbon capture and storage; EW: electrowinning; H2-DRI: hydrogen-based direct reduction; NG-DRI: natural gas-based direct reduction; scrap-EAF: scrap-based electric arc furnace; TGR-BF-BOF: top gas recycling blast-furnace and basic-oxygen furnace.

CCS technologies can reduce the net emission intensity of BF-BOF, TGR-BF-BOF, and NG-DRI by 15–46%, capturing 0.42–0.77 kg CO_2-eq./kg steel. Among them, NG-DRI-CCS achieves the lowest emission intensity by 2060 of 0.32 kg CO_2-eq./kg steel. Nevertheless, EW and green H2-DRI offer greater emission reduction potentials of -95% and -89%, respectively, than the CCS technologies, which achieve a maximum of -49% (BF-BOF-CCS), -55% (TGR-BF-BOF-CCS), and -86% (NG-DRI-CCS).

For all technologies, direct emissions from the steel production process in the BOF or EAF are almost negligible.

Efficiency improvements are applied only to iron and steel production processes (red and black areas in Figure 4), whose emissions decrease marginally over time. The benefits of efficiency improvements are thus minor compared to the effect of the overall climate mitigation scenario, which considerably lowers the impacts of multiple sectors, and especially those of electrified technologies, i.e., their upstream emissions.

The share of impacts from iron sinter and iron ore pellets, i.e., the iron-bearing materials for iron production, differs considerably among the routes, with high shares (17-38%) for BF-based and TGR-BF-based routes. The reason is that their iron production processes primarily use iron sinter, while the others use iron ore pellets (apart from EW, which directly uses iron ore concentrates). Iron sinter production has a considerably higher emission intensity than iron pellets (about a factor of 5) due to higher direct and indirect emissions (see ESI Section S2.1).

5.3.2. Future climate change impacts of global steel production

Impact by steel types and regions per kg of steel

Figure 6.a) illustrates the climate change impacts per kilogram of steel across various steel types and the global average (represented by the black line), which aggregates data from all six types (refer to Sections 5.2.2, S1.4.3). As anticipated, more ambitious climate scenarios lead to higher reductions in emissions. Under the 3.5°C scenario, impacts decrease by 33%, from 2.1 to 1.41 kg CO_2-eq./kg of steel (black line). While the 2°C scenario achieves a 56% reduction lowering emissions to 0.93 kg CO_2-eq./kg of steel, the 1.5°C scenario realizes the most substantial reduction of 79% to 0.44 kg CO_2-eq./kg of steel.

The trends are consistent across different steel types (e.g., low-alloyed, reinforcing, chromium steel), with only minor deviations. However, chromium steel stands out with significantly higher climate change impacts, exceeding the average by more than a factor of two (2.3–5.2 kg CO_2-eq./kg steel). This is primarily due to the energy-intensive production of its alloying elements, ferronickel and ferrochromium, which account for 56% and 25% of chromium steel's emissions in 2020, respectively. Hot rolling increases emissions by up to 14%, but its impact decreases under stricter climate goals from 0.27 to 0.06 kg CO_2-eq./kg of steel.

Figure 6.b) illustrates the regional differences in GHG emissions using the example of unalloyed steel and the top ten steel-producing regions. These originate from the region-specific steel production mixes (ESI Section S1.2.3), efficiency improvements (Section

S1.2.4), and regionalised scenarios for the upstream sectors, such as electricity or fuel supply.

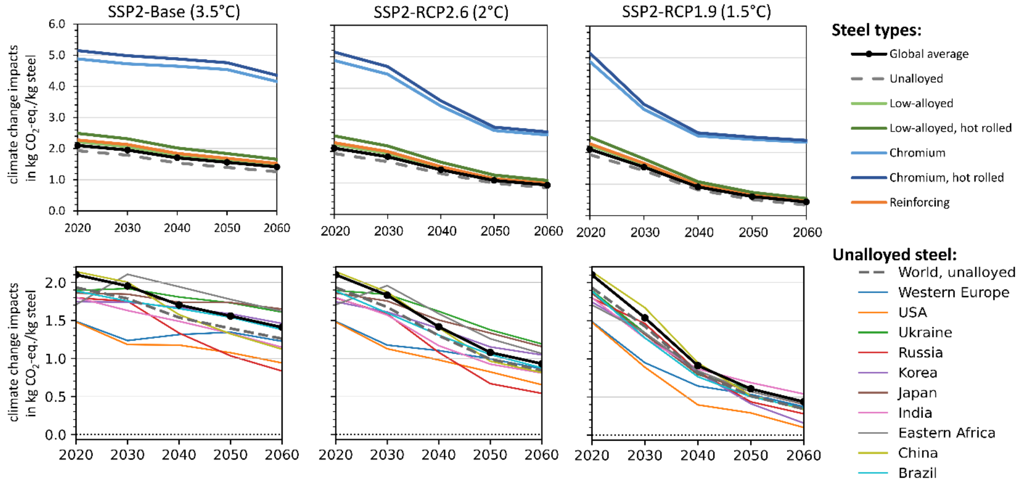


Figure 6: Specific climate change impacts of global steel production under the three scenarios: a) by steel type; b) for unalloyed steel for the top 10 producing regions. The global average steel (black line) represents the impacts of global steel supply summarizing the six steel types (e.g., low-alloyed, reinforcing steel, etc., ESI Section S1.4.3). RCP: Representative Concentration Pathways; SSP: Shared Socioeconomic Pathways.

Impacts of global steel production

Figure 7 illustrates annual climate change impacts of global steel production, with a +61% increase in production by 2060 in our scenarios.

Figure 7.a) shows that annual GHG emissions strongly depend on the scenario. In the Base scenario, they rise by 8% in 2060 compared to 2020, i.e., from the current 3.4 Gt CO_2-eq./year to 3.7 Gt CO_2-eq./year (Figure 7.b). Under stricter decarbonization measures the declining GHG emission intensity is sufficient to compensate for growing demand: total GHG emissions decrease by -29% (to 2.5 Gt CO_2-eq./year) under the 2°C- and by -67% (to 1.2 Gt CO_2-eq./year) under the 1.5°C scenario by 2060. The substantial reductions in emission intensities achieve absolute decoupling of GHG emissions from demand growth. However, reaching net-zero emissions by 2050 or 2060 remains very challenging.

Unalloyed steel production accounts with 65-77% for the majority of global GHG emissions over time, provided its constant market share of 83% (Section 5.2.2). The other steel types contribute roughly equally between 3.8-9.9% (Figure 7.b).

Most emissions of unalloyed steel are currently associated with steel production via the BF-BOF (87%) (Figure 7.c). They decline considerably only with the introduction of new technologies in the 2°C scenario and are eliminated in the 1.5°C scenario. The residual emissions are primarily caused by the alternative technologies of TGR-BF-BOF in the 2°C scenario, and the TGR-BF-BOF-CCS in the 1.5°C scenario. The electrified technologies of EW and scrap-EAF have very low emissions in 2060 despite their high production shares in the 1.5°C scenario, which demonstrates their high emission reduction potential. In contrast, the insufficient benefit of mere efficiency improvements and the risk of a lock-in effect with fossil-fuel-based technologies like the BF-BOF, but also TGR-BF-BOF and TGR-BF-BOF-CCS becomes apparent. By the time the world should have realised net-zero emissions, such technologies would still emit 0.3 Gt CO_2-eq./year in the 1.5°C- and even 1.4 Gt CO_2-eq./year in the 2°C scenario in 2060 for unalloyed steel alone[4].

By 2060, the cumulative GHG emissions (red line in Figure 7.c) of the Base scenario (151 Gt CO_2-eq. in 2060) can only marginally be reduced through the decarbonization scenarios by -18% to 124 Gt CO_2-eq. (2°C) and by -41% to 89 Gt CO_2-eq. (1.5°C). The Intergovernmental Panel on Climate Change (IPCC) provides remaining global carbon budgets from 2020 to the end of the century of 900-1350 Gt CO_2-eq. and 300-500 Gt CO_2-eq. for the 2°C and 1.5°C scenarios and 50-83% likelihoods (IPCC, 2021). The steel industry would thus consume between 9-14% (2°C scenario) and 18-30% (1.5°C scenario) of these global end-of-the-century carbon budgets by 2060.

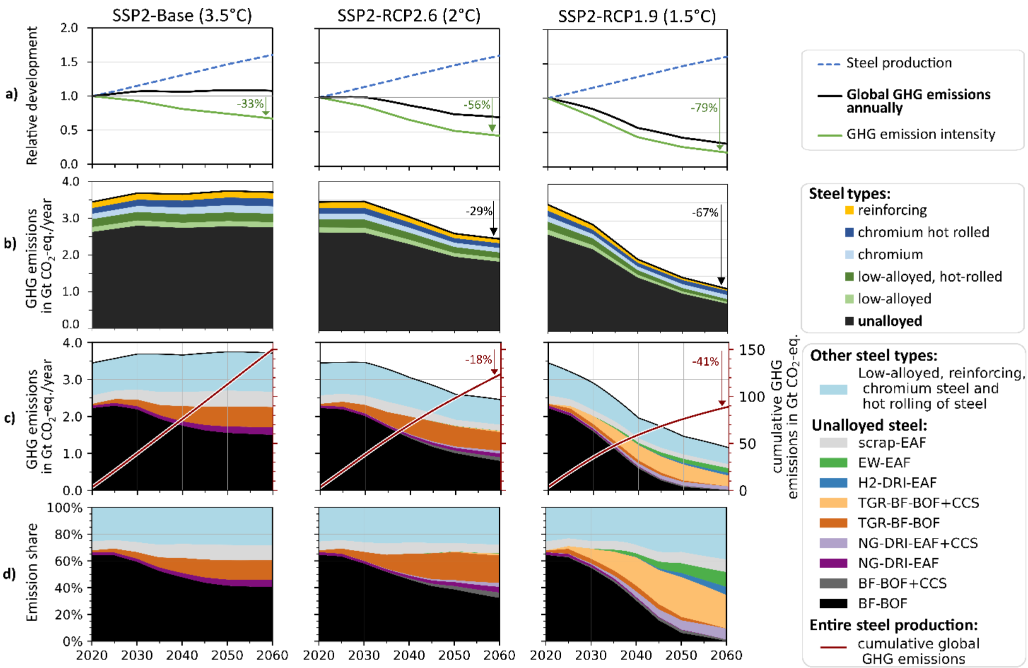


Figure 7: Annual and cumulative climate change impacts of global steel supply if future production amounts are considered; a) development relative to 2020; b) distinguished by steel type; c) distinguished by production technology for unalloyed steel with cumulative global GHG emissions (right y-axis); d) relative by production technology for unalloyed steel. Functional unit: global steel production from the global market group for steel; premise: all background scenarios are incorporated. BF-BOF: blast-furnace and basic-oxygen furnace; CCS: carbon capture and storage; EW: electrowinning; H2-DRI: hydrogen-based direct reduction; NG-DRI: natural gas-based direct reduction; RCP: Representative Concentration Pathways; scrap-EAF: scrap-based electric arc furnace; SSP: Shared Socioeconomic Pathways; TGR-BF-BOF: top gas recycling blast-furnace and basic-oxygen furnace.

[4] Emission sums for BF-BOF, BF-BOF-CCS, TGR-BF-BOF and TGR-BF-BOF-CCS for unalloyed steel.

5.3.3. Future non-climate environmental impacts of global steel production

Environmental impacts per kg of steel

Figure 8 illustrates the projected changes in environmental impacts per kilogram of steel produced for 16 impact categories in 2060 under the 1.5°C scenario relative to 2020. It highlights potential burden shifting, where reductions in climate change impacts (-79%) may come at the cost of increasing impacts in other categories. These are carcinogenic human toxicity (+25%), water use (+27%), land use (+79%), material resource depletion (+100%), ionising radiation (+241%), and ozone depletion (+275%).

The drivers of these impacts vary by category. Mining contributes to ecotoxicity and freshwater eutrophication, steel production processes drive human toxicity, water use, and ozone depletion, while upstream energy, especially electricity-generating processes dominate ionising radiation, material resource depletion and land use impacts (ESI Sections S2.2-S2.3). Transport contributes to marine and terrestrial eutrophication.

Higher electricity demand for electrified steel production intensifies ionising radiation impacts (+241%) caused by the assumed nuclear power generation, especially the uranium tailings treatment due to radon emissions to the air or chemicals leaking into groundwater (Schläger et al., 2016; U.S. Department of Energy, 2016). These emissions may be lowered, for instance, by covering tailings with clay (U.S. Department of Energy, 2016) or installing lining membranes and water management systems for tailing deposits. Carbon-14 is released from the treatment of spent nuclear fuel.

Likewise, land use impacts (+79%) increase due to biomass-based power generation which is controversial as it competes with food production, nature conservation (Birdsey et al., 2018; Rulli et al., 2016; Yang et al., 2021), and biomass-based fuels for other sectors, such as cement (Müller et al., 2024). Holistic assessments across sectors are needed to evaluate the availability of renewable electricity and sustainable biomass supply, considering natural limits.

The increase in material resource depletion (+100%) is driven by a higher demand for metals required for more electrified steel and more renewable power systems (e.g., for PV and wind turbines) by 2060, such as tellurium, copper, gold and silver, and sodium chloride for sodium hydroxide (for EW). Chromium for chromium steel has a high contribution (21-40%), but its impact stays about constant. Metal depletion could be reduced by more sustainable metal cycles, limiting primary metal extraction. Generally, the energy transition is expected to decrease overall mining activity globally (Nijnens et al., 2023).

The future impacts of ozone depletion and carcinogenic human toxicity might be overestimated. Ozone depletion (+275%), currently driven by coke production, may rise due to sodium hydroxide production, the alkaline electrolyte required for EW. However, the impacts caused by refrigerant gas leaks are likely lower in the future due to ongoing phase-outs of ozone-depleting gases under the Montreal Protocol (Heath, 2017; van den Oever et al., 2024). Carcinogenic human toxicity (+25%) stems from two main processes: i) chromium emissions into water due to landfilled EAF slag, which has also been reported by previous studies using current ecoinvent processes (Reinhard et al., 2019; Schenker et al., 2022); and ii) benzo(a)pyrene emissions from coke production. Landfilling EAF slag will probably decline with stricter regulations and when reusing and recovering materials from slag becomes more common. Since slag treatment was modelled based on scrap-EAFs due to a lack of primary data for EAFs used for primary production, slag-related impacts might be overestimated. Nevertheless, the use of EAFs for primary and secondary production will increase in the future, highlighting the need to improve slag management.

For some categories, such as water use (+27%), multiple processes contribute without a dominant source.

On the other hand, several impacts are expected to decline in the future since they co-benefit from the phase-out of coal- and coke-based processes, along with BF-BOFs: ecotoxicity (-23%), eutrophication (-35 – 69%), acidification (-42%), particulate matter (-43%), and photochemical ozone formation (-52%). Their primary contributors include coal mining, coke production, production of iron sinter, and, for example, the treatment of spoil from coal mining and BOF slags in landfills (e.g., freshwater eutrophication).

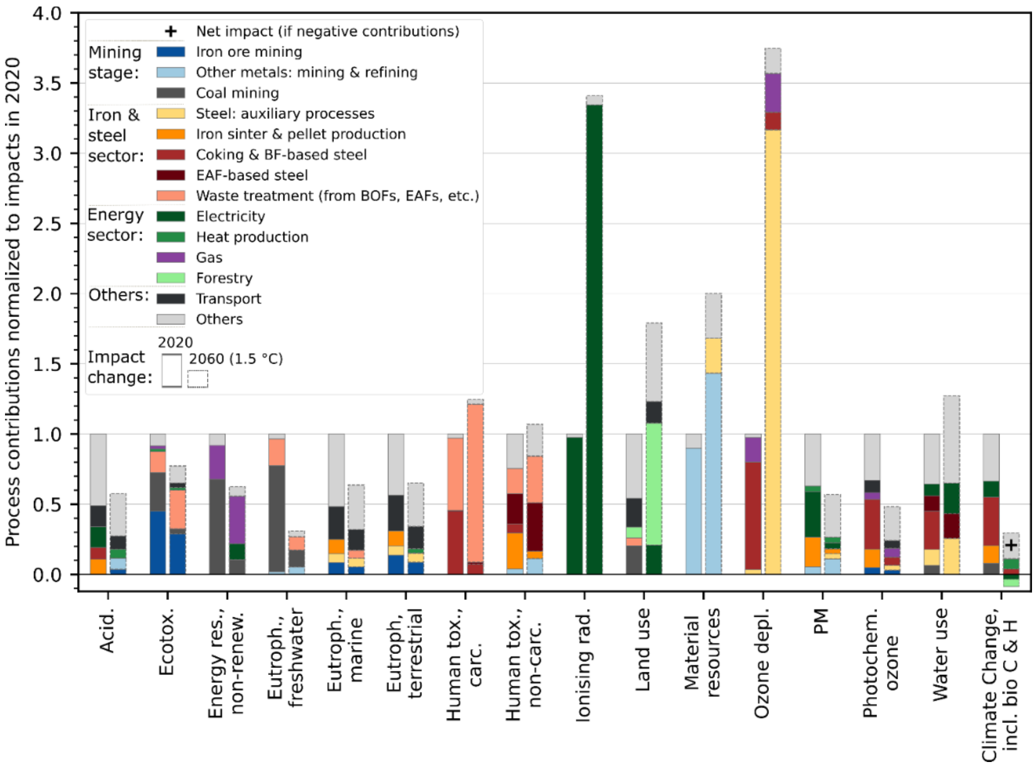


Figure 8: Impact development and contribution analysis of impacts in 2060 relative to 2020 per kg steel for 16 impact categories. Values are given for 2060 in the 1.5°C scenario (right bar) relative to 2020 (left bar). The top 5 contributors were selected, aggregated by process name, and partly manually grouped. Functional unit: 1 kg of steel from the global market group for steel, premise: all background scenarios are incorporated. Further results are provided in the ESI, Section S2.2-S2.3. Acid.: acidification; Ecotox.: ecotoxicity; Energy res., non-renew.: non-renewable energy resources; Eutroph., freshwater: freshwater eutrophication; Eutroph., marine: marine eutrophication; Eutroph, terrestrial: terrestrial eutrophication; Human tox., carc.: carcinogenic human toxicity; Human tox., non-carc.: non-carcinogenic human toxicity; Ionising rad.: ionising radiation; Ozone depl.: ozone depletion; PM: particulate matter; Photochem. ozone: photochemical ozone formation; incl. bio C & H: including biogenic carbon and hydrogen.

Environmental impacts of global steel production

Figure 9 shows the change of annual impacts by 2060, when rising future global steel production is considered (+61% by 2060). It demonstrates that impacts may increase in most impact categories. Impacts per kg of steel would need to decline by at least -38% by 2060 to compensate for the effect of rising demand. Thus, the impact reduction on a per kg steel basis is insufficient to compensate for growing demand, e.g., for ecotoxicity. While the decarbonization scenarios can achieve a decoupling for climate change impacts, an absolute decoupling cannot be observed for many other impact categories.

Impact categories benefitting from the BF-BOF phase-out exhibit a different trend, showing approximately constant or decreasing impacts. These are acidification (-7%), eutrophication (-50%), particulate matter (-8%), and photochemical ozone formation (-22%). However, they decline to a lesser extent than climate change (-67%).

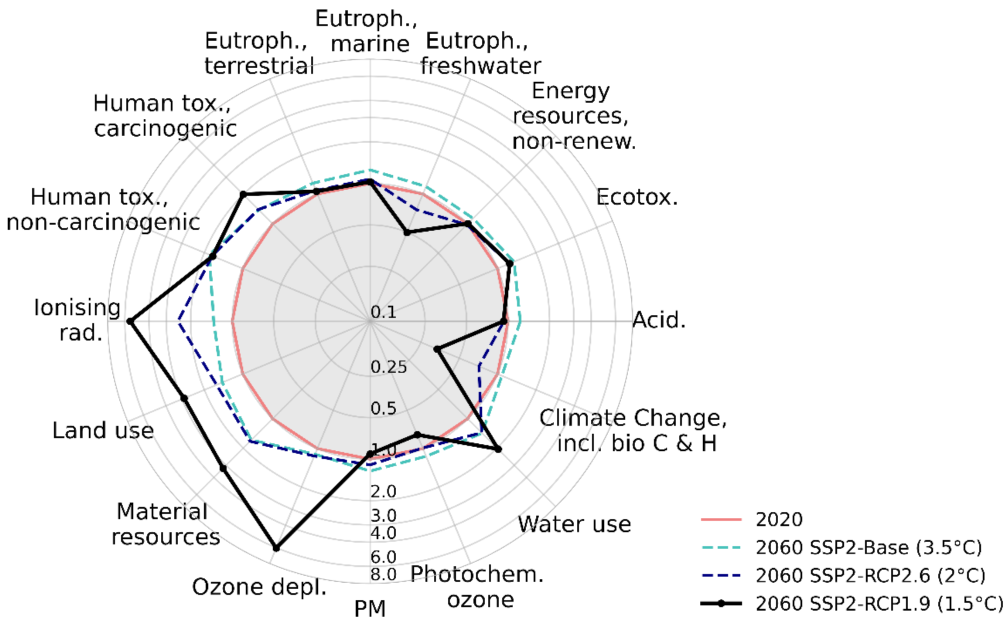


Figure 9: Impact development of global steel production in 2060 compared to 2020 for total impacts considering annual global steel production. Values are relative to the impacts in 2020 on a logarithmic scale. Functional unit: global annual steel production from the global market for steel; premise: all background scenarios are incorporated. For results per steel type, see ESI Section S2.2. Acid.: acidification; Ecotox.: ecotoxicity; Energy res., non-renew.: non-renewable energy resources; Eutroph., freshwater: freshwater eutrophication; Eutroph., marine: marine eutrophication; Eutroph, terrestrial: terrestrial eutrophication; Human tox., carc.: carcinogenic human toxicity; Human tox., non-carc.: non-carcinogenic human toxicity; Ionising rad.: ionising radiation; Ozone depl.: ozone depletion; PM: particulate matter; Photochem. ozone: photochemical ozone formation; RCP: Representative Concentration Pathways; SSP: Shared Socioeconomic Pathways; incl. bio C & H: including biogenic carbon and hydrogen.

5.4. Discussion

5.4.1. The cumulative GHG emission reduction is insufficient

Even under the most ambitious 1.5°C scenario, the steel sector's cumulative GHG emissions are reduced by only -41% by 2060 compared to the 3.5°C Base scenario. The 2°C scenario achieves a modest reduction of cumulative GHG emissions of-18%. As a result, steel production would 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 the steel sector (Harpprecht, Naegler, Steubing, Tukker, & Simon, 2022; P. Wang et al., 2021; Yokoi et al., 2022). For other hard-to-abate sectors, such as cement (Müller et al., 2024), similar results were found: Müller et al. (2024) estimated cumulative GHG emissions for cement production ranging from 56 to 129 Gt CO_2. This suggests that cement and steel production combined would account for 29–48% of the 1.5°C or 14–21% of the 2°C end-of-the-century carbon budget by 2060.

Neither the steel nor the cement sector achieves net-zero emissions by 2060, and hence will claim additional portions of the remaining carbon budget beyond this timeframe. Even electrified technologies like EW and scrap-EAF have remaining emissions of 0.12 kg CO_2-eq./kg of steel by 2060.

For steel production, particularly the lock-in created by coke-based and CCS technologies (BF-BOF-CCS and TGR-BF-BOF-(CCS) is problematic. Our analysis shows these can reduce emissions in the short term with CCS enabling retrofitting of modern existing plants. However, their emission reduction potential is insufficient in the long term. Investments in CCS will create significant sunk costs for new and long-term infrastructure for CO_2 capture and storage facilities, leading to an incentive to use this infrastructure for decades.

If primary production were to shift entirely to green H2-DRI to replace BF-BOFs, which are phased out as described in the 1.5°C scenario, cumulative GHG emissions could be further reduced by approximately 15% by 2060 compared to the 1.5°C scenario, based on estimates for unalloyed steel (ESI S3.1). Yet, this represents only a marginal improvement. Thus, the sector needs to realise faster and more drastic decarbonization and emission reduction that exceed those projected in our scenarios.

5.4.2. System-wide reduction options beyond our projections must be found

Options to further reduce emissions include:

- reducing demand, particularly for emission-intensive primary steel production, through means such as a circular economy, material substitution, or by increasing life-times and material efficiencies;
- accelerating technological development and large-scale implementation of green technologies with the highest emission reduction potential, namely, H2-DRI and EW, while simultaneously scaling-up infrastructure for green electricity and hydrogen;
- accelerating the decommissioning of inefficient and emission-intensive facilities of BF-BOFs, while also avoiding constructing new capacities for them;

- replacing BF-BOFs with NG-DRI soon, as it is a mature technology of lower emission intensity than BF-BOFs. The advantage of this strategy is that NG-DRI furnaces can switch to near zero-emission H2-DRI when sufficient green hydrogen becomes available, which avoids the lock-in effects of CCS described above.
- Next to demand-side reduction strategies, these options essentially imply an ambitious (indirect) electrification of the steel sector and its supply chains. Impacts will shift away from the direct steel production (like BF-BOF) to indirect sources, especially electricity and hydrogen supply, e.g., for H2-DRI and EW, a finding consistent with previous research (Weckenborg et al., 2024). The benefit of ambitious electrified steel scenarios becomes effective only if the electricity sector is also decarbonized, as demonstrated by an analysis in the ESI (Section S2.4). The multi-sector perspective and life-cycle-based approach applied here is hence essential to identify optimal solutions.

The suggested strategies may not be readily adopted without additional economic incentives because of high investment and energy costs, e.g., for hydrogen, natural gas or green electricity. Moreover, green hydrogen and electricity will likely be limited in the future, with other sectors competing for them (Harpprecht, Naegler, Steubing, Tukker, & Simon, 2022; Watari et al., 2023; Watari & McLellan, 2024). Further research is needed to assess the effect and feasibility of such measures, and to identify suitable policies.

5.4.3. Potential trade-offs of decarbonisation require multi-sectoral measures

Electrifying the steel sector with decarbonized power cannot mitigate impacts in all categories. Hotspots depend on the impact category (see Sections 5.3.3., S2.4).

Our life cycle assessment of IMAGE scenarios revealed both co-benefits and burden-shifting of decarbonisation measures. The 1.5°C scenario changes impacts the most, albeit in either direction, which demonstrates potential trade-offs of future decarbonization strategies, as explained below.

On a per-kg steel basis decarbonizing steel supply can achieve co-benefits in key impact categories for air quality, like particulate matter (-43%) or photochemical ozone formation (-52%). This is vital since air pollution, a global problem, is considered the leading environmental threat to human health (WHO, 2021). Moreover, it can lower harm to ecosystems through reduced ecotoxicity (-23%), water eutrophication (-35–69%), and acidification (-42%), which are pressing issues near mines or industrial sites (Northey et al., 2016; Schenker et al., 2022; Sonter et al., 2018; Sonter et al., 2017).

Impacts may shift to non-climate impact categories, i.e., ionising radiation (+241%), metal resources (+100%), land use (+79%), carcinogenic human toxicity (+25%), and water use (+27%), on a per-kg steel basis (Figure 8). Rising impacts in these categories were also identified for decarbonization scenarios of other sectors, e.g., cement (Müller et al., 2024), hydrogen (Wei et al., 2024) or ammonia (Boyce et al., 2024). The absolute values of these rising impacts are subject to uncertainty due to data limitations and the lack of scenario data in the background database, as explained earlier (Section 5.3.3). While impacts in carcinogenic human toxicity (+25%) and ozone depletion (+275%) are likely overestimated, the trend of increasing impacts in ionising radiation, metal depletion, and land use is plausible as they are driven by electricity supply. It is thus understandable that these impacts will rise with higher electricity demand for a more electrified steel production. However, they are determined by the assumed electricity supply mix, which here includes, e.g., nuclear power, and may thus be reduced under a different electricity mix.

When considering future growth in global steel production, our scenarios indicate that the impacts of total steel production globally will rise in most categories. Impacts may decline only for GHG emissions, acidification, freshwater eutrophication, particulate matter, and photochemical ozone formation.

A tentative normalisation and weighting exercise show that the steel sector's non-climate impacts could play a non-negligible role compared to climate change (ESI Section S2.5). Despite the uncertainty inherent to normalisation and weighting (Pizzol et al., 2017), this underscores the importance of considering impacts beyond climate change for future steel production, as also emphasized in previous research (Schenker et al., 2022; Watari et al., 2021).

5.4.4. Understanding environmental impacts at the global and local scale is crucial

In sum, our scenarios do not achieve an absolute decoupling across all impact categories from a global perspective. Such absolute decoupling is generally required to sustain ecosystem quality (Vadén et al., 2020). Our finding aligns with historic trends where absolute decoupling was only partially observed, e.g., for certain emissions to air but not for all environmental impacts (Vadén et al., 2020), as well as with scenario assessments for other metals, such as nickel or zinc (Harpprecht et al., 2024; Yokoi et al., 2022).

While this emphasizes the urgency of minimizing future primary production and the relevance of impact assessments with a global scope, regional assessments are equally crucial. Certain impacts are particularly relevant locally, such as freshwater use, particulate matter or water eutrophication (Schenker et al., 2022; Steffen et al., 2015). For instance, the rise in water use (+105%) for steel production may be considered minor at the global level, where the primary freshwater consumer is the agricultural sector, requiring about 70% of water globally (B. Otto & Schleifer, 2020). Yet, mining and industrial activities can be highly problematic in regions of water scarcity (Northey et al., 2016; Schenker et al., 2022).

Future research should identify process- and impact-category-specific emission prevention measures and targeted policies to minimize trade-offs, avoid unwanted side-effects and achieve decoupling (Schandl et al., 2016). To better prioritise such interventions, we recommend assessing the relevance of each impact category at both global and local levels, e.g., using frameworks like planetary boundaries (Schenker et al., 2022; Steffen et al., 2015) or regionalized impact assessment (Hellweg et al., 2023). Defining and allocating the respective impact threshold is subject to future research. Comprehensive models with a sufficient spatial resolution are essential to link demand and supply scenarios and to account for future emissions of other sectors.

5.4.5. Limitations and future research

When interpreting shares of carbon budgets, the approach emissions were calculated needs to be considered: i) we quantified life cycle emissions, which includes indirect emissions of upstream processes, e.g., from electricity or hydrogen supply, while the accounting system of the IPCC differentiates between more sectors; ii) although we integrated scenarios for several sectors via premise, background scenarios for other sectors and supply chains are still lacking in the LCA model, e.g., for chromium steel, electrolyte or generally chemicals production. The latter may lead to overestimating future impacts, but could be addressed by including scenarios for additional sectors.

Utilizing large global integrated assessment models as a guide for future change has proven fruitful for global impact assessment. However, the formulations of such modelling frameworks imply various general limitations and uncertainties inherent to scenario assessments (as discussed in detail in the ESI section S3.2.1). As such, the scenarios should not be interpreted as accurate predictions but as exploratory, i.e., what-if scenarios, providing insights into directions of future developments, their consequences, and venues for further research:

- **Need for ex-ante socio-technical analysis on diffusion and adoption patterns of technologies:** The model framework uses multiple abstracted representations of sectors and an exhaustive portfolio of incumbent and novel technologies, which are parameterised according to empirical analysis or expert consultations (as demonstrated in prior studies (van Sluisveld et al., 2021; van Sluisveld et al., 2018; van Sluisveld et al., 2020)). Model results depict the outcome of the interaction of these portfolios under specific constraints and rule-sets, which may lead to counterintuitive results, such as the scenarios' reliance on CCS, nuclear power and negative GHG emissions for bio-based electricity generation. Similarly, EW, characterised by a low technology readiness level (TRL 4-5 (IEA, 2025)), outcompetes (blue) H2-DRI (TRL 6-8 (IEA, 2025)) under stringent emission targets, as illustrated in the 1.5°C scenario, since the assumed increasing carbon tax creates a landscape that advances this more expensive technology due to its lower GHG footprint than H2-DRI (Figure 5). Although this drastic transition to EW may seem counterintuitive, it reveals the limited GHG emission reduction potential even under such an ambitious scenario. Further ex-ante analyses on the socio-technical development pathways for various production systems (e.g., via green H2, EW) could help underpin specific (regional) adoption and diffusion patterns.
- **Focus beyond CO_2:** As steel demand growth primarily drives the presented impacts, additional production and consumption pathways should be explored to gain deeper insights into future emissions. Options to consider are, e.g., scenarios with higher shares of secondary production and green H2-DRI, exploring other novel technologies and electricity supply scenarios, or applying multi-objective optimisation considering impact categories beyond CO_2.
- **Focus beyond aggregated production systems:** More detailed metal scenarios are needed, e.g., accounting for the demand for emission-intensive steel types and alloys

alongside decarbonization options for energy-intensive alloying elements (Elshkaki et al., 2017; Nuss et al., 2014), such as chromium and ferronickel, the suitability of novel production routes for certain steel types, the effect of mixed inputs of primary iron and scrap into BOFs and EAFs, or considering trade, e.g., of green primary iron from H2-DRI or EW (Bilici et al., 2024).

Expanding the scope of the scenarios and assessment could be achieved by integrating other modelling frameworks, e.g., offering higher technological, regional or economic resolution.

Likewise, the LCIs of steel production technologies could be further refined to increase data quality, considering, e.g., the scale-up effects of electrowinning potentially lowering sodium hydroxide requirements, a shift to green sodium hydroxide production, waste treatment processes, detailed emissions of electric arc furnaces operated with primary material from H2-DRI or EW, or generally the effect of emission mitigation measures. Further modelling assumptions and associated limitations are provided in the ESI, Section S3.2. We published our data and Python code openly in a repository to facilitate future studies (Harpprecht et al., 2025).

5.5. Conclusions

This study assessed a broad spectrum of the future life-cycle-based environmental impacts of global steel production. We coupled state-of-the-art LCA models of current and future steel production routes with multi-sectoral, internally consistent scenarios for future energy and steel supply from the integrated assessment model IMAGE for three climate targets: 3.5°C, <2°C, and 1.5°C. Our assessment considers nine steel production routes, including CCS options and novel technologies for hydrogen- and electricity-based iron production (H2-DRI and EW). The main outcomes of this study are:

Net-zero steel production unlikely to be reached by 2060

Compared to the current coke-based BF-BOF route, specific life-cycle-based GHG emissions can be minimized by up to 95% by the electrified technologies of H2-DRI, EW and secondary production if green power is used. These technologies still have residual emissions, but outperform CCS technologies for BF-BOFs. However, even in the most optimistic 1.5°C scenario, electrified technologies are unlikely to fulfil the global steel demand by 2060. Hence, global steel production's average life-cycle GHG emission intensity decreases by only 79% by 2060 in this scenario, falling short of climate neutrality. Considering the 61% increase in global steel production from 2020 to 2060, annual global steel-related GHG emissions may be reduced by at most 67% by 2060. Cumulative emissions are 41% lower in the 1.5°C than in the Base scenario (Sections 5.3.1-5.3.2).

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

The steel sector's transition in the scenarios assessed is overall too slow and may still contribute 89-151 Gt CO_2-eq. until 2060, which represents 9-14% (2°C scenario) and even 18-30% (1.5°C) of the respective end-of-the-century global carbon budgets (Section 5.3.2). Hence, faster technological development and large-scale implementation of green technologies are required, e.g., for H2-DRI and EW, while simultaneously lowering steel demand and ramping up the supply infrastructure for renewable electricity and green hydrogen. Deploying CCS to (TGR-)BF-BOF plants poses the risk of a lock-in effect, as the emission reduction potential is insufficient and may delay the transition to steel production of lower emission intensity.

Decarbonizing steel production may shift burdens to other processes that enhance non-climate change impacts

An electrification of steel production is likely to increase impacts (per ton of steel) on land use, material resource depletion, and ionising radiation, which are driven by the assumed future electricity mix (Section 5.3.3). If steel demand continues to rise, the global impacts of decarbonized steel production may increase in more categories, such as human toxicity and water use (Section 5.3.3).

However, certain impact categories also benefit from the phase-out of coke-based processes and may therefore decrease overall. These are acidification, freshwater eutrophication, particulate matter, and photochemical ozone formation (Section 5.3.3).

As the emission hotspots of steel production are diverse and depend on the impact category, targeted interventions across the entire supply chain are required to further decrease emissions (Section 5.3.3). Measures include responsible sourcing of energy carriers and materials, such as electricity, green iron, or sodium hydroxide, and improving slag and mining waste management practices.

Further insights into additional emission reduction levers required

Future research is required to identify additional options to reduce GHG emissions of iron and steel production faster, while also avoiding burden shifting to other categories. This includes exploring potential emission mitigation technologies, alternative steel and energy supply scenarios, additional levers for impact reduction, such as minimising primary steel production, and assessing the relevance of adverse side effects at global and regional levels, e.g., using frameworks like planetary boundaries. Our study can provide a basis for such future works.

References

Arens, M., Worrell, E., Eichhammer, W., Hasanbeigi, A., & Zhang, Q [Qi] (2017). Pathways to a low-carbon iron and steel industry in the medium-term – the case of Germany. *Journal of Cleaner Production*, *163*, 84–98. https://doi.org/10.1016/j.jclepro.2015.12.097

Baumstark, L., Bauer, N., Benke, F., Bertram, C., Bi, S., Gong, C. C., Dietrich, J. P., Dirnaichner, A., Giannousakis, A., Hilaire, J., Klein, D., Koch, J., Leimbach, M., Levesque, A., Madeddu, S., Malik, A., Merfort, A., Merfort, L., Odenweller, A., . . . Luderer, G. (2021). REMIND2.1: Transformation and innovation dynamics of the energy-economic system within climate and sustainability limits. *Geoscientific Model Development.* Advance online publication. https://doi.org/10.5194/gmd-14-6571-2021

Beer, J. de, Harnisch, J., & Kerssemeeckers, M. (2000). *Greenhouse gas emissions from major industrial sources - III Iron and steel production.* the Netherlands, ECOFYS.

Bhaskar, A., Assadi, M., & Nikpey Somehsaraei, H. (2020). Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen. *Energies*, *13*(3). https://doi.org/10.3390/en13030758

Bilici, S., Holtz, G., Jülich, A., König, R., Li, Z [Zhenxi], Trollip, H., Call, B. M., Tönjes, A., Vishwanathan, S. S., Zelt, O., Lechtenböhmer, S., Kronshage, S., & Meurer, A. (2024). Global trade of green iron as a game changer for a near-zero global steel industry? - A scenario-based assessment of regionalized impacts. *Energy and Climate Change*, *5*, 100161. https://doi.org/10.1016/j.egycc.2024.100161

Birdsey, R., Duffy, P., Smyth, C., Kurz, W. A., Dugan, A. J., & Houghton, R. (2018). Climate, economic, and environmental impacts of producing wood for bioenergy. *Environmental Research Letters*, *13*(5), 50201. https://doi.org/10.1088/1748-9326/aab9d5

Boyce, J., Sacchi, R., Goetheer, E., & Steubing, B. (2024). A prospective life cycle assessment of global ammonia decarbonisation scenarios. *Heliyon*, *10*(6), e27547. https://doi.org/10.1016/j.heliyon.2024.e27547

Chisalita, D.-A., Petrescu, L., Cobden, P., van Dijk, H. A. J., Cormos, A.-M., & Cormos, C.-C. (2019). Assessing the environmental impact of an integrated steel mill with post-combustion CO_2 capture and storage using the LCA methodology. *Journal of Cleaner Production*, *211*, 1015–1025. https://doi.org/10.1016/j.jclepro.2018.11.256

Choi, H.-D. (2013). *Hybrid life cycle assessment of steel production with carbon capture and storage*. Master Thesis. NTNU. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/235312

Cox, B., Mutel, C. L., Bauer, C., Mendoza Beltran, A., & van Vuuren, D. P. (2018). Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles. *Environ Sci Technol*, *52*(8), 4989–4995. https://doi.org/10.1021/acs.est.8b00261

EC. (2016). *Iron production by electrochemical reduction of its oxide for high CO_2 mitigation. IERO final report, European Commission.* https://op.europa.eu/en/publication-detail/-/publication/4255cd56-9a96-11e6-9bca-01aa75ed71a1 https://doi.org/10.2777/084034

Edelenbosch, O. Y., Kermeli, K., Crijns-Graus, W., Worrell, E., Bibas, R., Fais, B., Fujimori, S [S.], Kyle, P., Sano, F., & van Vuuren, D. P. (2017). Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. *Energy*, *122*, 701–710. https://doi.org/10.1016/j.energy.2017.01.017

Elshkaki, A., Reck, B. K., & Graedel, T. E. (2017). Anthropogenic nickel supply, demand, and associated energy and water use. *Resources, Conservation and Recycling*, *125*, 300–307. https://doi.org/10.1016/j.resconrec.2017.07.002

Fazio, S., Biganzioli, F., Laurentiis, V. de, Zampori, L., Sala, S., & Diaconu, E. (2018). *Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods: Version 2 from ILCD to EF3.0*. https://eplca.jrc.ec.europa.eu/permalink/TR_SupportingCF_FINAL.pdf https://doi.org/10.2760/002447

Fischedick, M., Marzinkowski, J., Winzer, P., & Weigel, M. (2014). Techno-economic evaluation of innovative steel production technologies. *Journal of Cleaner Production*, *84*, 563–580. https://doi.org/10.1016/j.jclepro.2014.05.063

Harpprecht, C., Miranda Xicotencatl, B., van Nielen, S., van der Meide, M., Li, C., Li, Z [Zhijie], Tukker, A., & Steubing, B. (2024). Future environmental impacts of metals: A systematic review of impact trends, modelling approaches, and challenges. *Resources, Conservation and Recycling*, *205*, 107572. https://doi.org/10.1016/j.resconrec.2024.107572

Harpprecht, C., Naegler, T., Steubing, B., & Sacchi, R. (2022). *Prospective Life Cycle Assessment of the Electricity-Based Primary Steel Production Technology of Electrowinning.* https://elib.dlr.de/191406/

Harpprecht, C., Naegler, T., Steubing, B., Tukker, A., & Simon, S. (2022). Decarbonization scenarios for the iron and steel industry in context of a sectoral carbon budget: Germany as a case study. *Journal of Cleaner Production*, *380*, 134846. https://doi.org/10.1016/j.jclepro.2022.134846

Harpprecht, C., Sacchi, R., Naegler, T., van Sluisveld, M., Daioglou, V., Tukker, A., & Steubing, B. (2025). *Code and data for publication: Future Environmental Impacts of Global Iron and Steel Production. v1.0.0*. https://doi.org/10.5281/zenodo.14968094 https://doi.org/10.5281/zenodo.14968094

Heath, E. A. (2017). Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (Kigali Amendment). *International Legal Materials*, *56*(1), 193–205. https://doi.org/10.1017/ilm.2016.2

Hellweg, S., Benetto, E., Huijbregts, M. A. J., Verones, F., & Wood, R. (2023). Life-cycle assessment to guide solutions for the triple planetary crisis. *Nature Reviews Earth & Environment*, *4*(7), 471–486. https://doi.org/10.1038/s43017-023-00449-2

Ho, M. T., Allinson, G. W., & Wiley, D. E. (2008). Reducing the Cost of CO 2 Capture from Flue Gases Using Membrane Technology. *Industrial & Engineering Chemistry Research*, *47*(5), 1562–1568. https://doi.org/10.1021/ie070541y

Hölling, M., & Gellert, S. (2018). Direct Reduction: Transition from Natural Gas to Hydrogen?

IEA. (2020). *Iron and Steel Technology Roadmap. Towards more sustainable steelmaking.* International Energy Agency.

IEA. (2025). *ETP Clean Energy Technology Guide*. https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide

IEAGHG (2013). Iron and Steel CCS Study (Techno-economics Integrated Steel Mill). Report 2013/04.

IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.*

IRP. (2019). *Global Resources Outlook 2019: Natural Resources for the Future We Want*. A Report of the International Resource Panel. United Nations Environment Programme. United Nations Environment Programme. https://www.un-ilibrary.org/content/books/9789280737417 https://doi.org/10.18356/689a1a17-en

ISO (2006). *DIN EN ISO 14040:* Environmental management – Life cycle assessment – Principles and framework. DIN Deutsches Institut für Normung e.V.

Keys, A., van Hout, M., & Daniëls, B. (2019, November 25). *Decarbonisation options for the Dutch Steel Industry.* PBL Netherlands Environmental Assessment Agency & ECN part of TNO. https://www.pbl.nl/sites/default/files/downloads/pbl-2019-decarbonisation-options-for-the-dutch-steel-industry_3723.pdf

Koroma, M. S., Brown, N., Cardellini, G., & Messagie, M. (2020). Prospective Environmental Impacts of Passenger Cars under Different Energy and Steel Production Scenarios. *Energies*, *13*(23). https://doi.org/10.3390/en13236236

Langkau, S., Steubing, B., Mutel, C., Ajie, M. P., Erdmann, L., Voglhuber-Slavinsky, A., & Janssen, M. (2023). A stepwise approach for Scenario-based Inventory Modelling for Prospective LCA (SIMPL). *The International Journal of Life Cycle Assessment*, *28*(9), 1169–1193. https://doi.org/10.1007/s11367-023-02175-9

Lavelaine, H. (2019). ΣIDERWIN project: electrification of primary steel production for direct CO_2 emission avoidance. *METEC, 2019*.

Lei, T., Wang, D., Yu, X., Ma, S., Zhao, W., Cui, C., Meng, J., Tao, S., & Guan, D. (2023). Global iron and steel plant CO_2 emissions and carbon-neutrality pathways. *Nature*, *622*(7983), 514–520. https://doi.org/10.1038/s41586-023-06486-7

Li, F., Chu, M., Tang, J., Liu, Z., Guo, J., Yan, R., & Liu, P. (2022). Thermodynamic performance analysis and environmental impact assessment of an integrated system for hydrogen generation and steelmaking. *Energy*, *241*, 122922. https://doi.org/10.1016/j.energy.2021.122922

Mendoza Beltran, A., Cox, B., Mutel, C., Vuuren, D. P., Font Vivanco, D., Deetman, S., Edelenbosch, O. Y., Guinée, J., & Tukker, A. (2018). When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment. *Journal of Industrial Ecology*, *24*(1), 64–79. https://doi.org/10.1111/jiec.12825

Moya, J. A., & Pardo, N. (2013). The potential for improvements in energy efficiency and CO_2 emissions in the EU27 iron and steel industry under different payback periods. *Journal of Cleaner Production*, *52*, 71–83. https://doi.org/10.1016/j.jclepro.2013.02.028

Müller, A., Harpprecht, C., Sacchi, R., Maes, B., van Sluisveld, M., Daioglou, V., Šavija, B., & Steubing, B. (2024). Decarbonizing the cement industry: Findings from coupling prospective life cycle assessment of clinker with integrated assessment model scenarios. *Journal of Cleaner Production*, *450*, 141884. https://doi.org/10.1016/j.jclepro.2024.141884

Nduagu, E. I., Yadav, D., Bhardwaj, N., Elango, S., Biswas, T., Banerjee, R., & Rajagopalan, S. (2022). Comparative life cycle assessment of natural gas and coal-based directly reduced iron (DRI) production: A case study for India. *Journal of Cleaner Production*, *347*, 131196. https://doi.org/10.1016/j.jclepro.2022.131196

Nijnens, J., Behrens, P., Kraan, O., Sprecher, B., & Kleijn, R. (2023). Energy transition will require substantially less mining than the current fossil system. *Joule*, *7*(11), 2408–2413. https://doi.org/10.1016/j.joule.2023.10.005

Northey, S. A., Mudd, G. M., Saarivuori, E., Wessman-Jääskeläinen, H., & Haque, N. (2016). Water footprinting and mining: Where are the limitations and opportunities? *Journal of Cleaner Production*, *135*, 1098–1116. https://doi.org/10.1016/j.jclepro.2016.07.024

Nuss, P., & Eckelman, M. J. (2014). Life cycle assessment of metals: a scientific synthesis. *PloS One*, *9*(7), e101298.

Nuss, P., Harper, E. M., Nassar, N. T., Reck, B. K., & Graedel, T. E. (2014). Criticality of iron and its principal alloying elements. *Environmental Science & Technology*, *48*(7), 4171–4177. https://doi.org/10.1021/es405044w

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

Otto, A., Robinius, M., Grube, T., Schiebahn, S., Praktiknjo, A., & Stolten, D. (2017). Power-to-Steel: Reducing CO_2 through the Integration of Renewable Energy and Hydrogen into the German Steel Industry. *Energies*, *10*(4). https://doi.org/10.3390/en10040451

Otto, B., & Schleifer, L. (2020). *Domestic Water Use Grew 600% Over the Past 50 Years*. https://www.wri.org/insights/domestic-water-use-grew-600-over-past-50-years

Pauliuk, S., Arvesen, A., Stadler, K., & Hertwich, E. G. (2017). Industrial ecology in integrated assessment models. *Nature Climate Change*, *7*(1), 13–20. https://doi.org/10.1038/nclimate3148

PBL. (2024). *IMAGE 3.3 Documentation.* Netherlands Environmental Assessment Agency.

Pizzol, M., Laurent, A., Sala, S., Weidema, B., Verones, F., & Koffler, C. (2017). Normalisation and weighting in life cycle assessment: quo vadis? *The International Journal of Life Cycle Assessment*, *22*(6), 853–866. https://doi.org/10.1007/s11367-016-1199-1

Quader, M. A., Ahmed, S., Dawal, S. Z., & Nukman, Y. (2016). Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO) Steelmaking (ULCOS) program. *Renewable and Sustainable Energy Reviews*, *55*, 537–549. https://doi.org/10.1016/j.rser.2015.10.101

Reinhard, J., Wernet, G., Zah, R., Heijungs, R., & Hilty, L. M. (2019). Contribution-based prioritization of LCI database improvements: the most important unit processes in ecoinvent. *The International Journal of Life Cycle Assessment*, *24*(10), 1778–1792. https://doi.org/10.1007/s11367-019-01602-0

Remus, R., Aguado-Monsonet, M. A., Roudier, S., & Sancho, L. D. (2013). *Best Available Techniques (BAT) reference document for iron and steel production: Industrial emissions directive 2010/75/EU: integrated pollution prevention and control (No. JRC69967).* Joint Research Centre (Seville). https://doi.org/10.2791/97469

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S [Shinichiro], Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., . . . Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rosner, F., Papadias, D., Brooks, K., Yoro, K., Ahluwalia, R., Autrey, T., & Breunig, H. (2023). Green steel: design and cost analysis of hydrogen-based direct iron reduction. *Energy & Environmental Science*, *16*(10), 4121–4134. https://doi.org/10.1039/D3EE01077E

Rulli, M. C., Bellomi, D., Cazzoli, A., Carolis, G. de, & D'Odorico, P. (2016). The water-land-food nexus of first-generation biofuels. *Scientific Reports*, *6*, 22521. https://doi.org/10.1038/srep22521

Ryan, N. A., Miller, S. A., Skerlos, S. J., & Cooper, D. R. (2020). Reducing CO_2 Emissions from U.S. Steel Consumption by 70% by 2050. *Environ Sci Technol*, *54*(22), 14598–14608. https://doi.org/10.1021/acs.est.0c04321

Sacchi, R., Terlouw, T., Dirnauchner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., & Luderer, G. (2021). PRospective EnvironMental Impact asSEment (premise): a streamlined approach to producing databases for prospective Life Cycle Assessment using Integrated Assessment Models. *Renewable and Sustainable Energy Reviews.* Advance online publication. https://doi.org/10.1016/j.rser.2022.112311

Sand, M., Skeie, R. B., Sandstad, M., Krishnan, S., Myhre, G., Bryant, H., Derwent, R., Hauglustaine, D., Paulot, F., Prather, M., & Stevenson, D. (2023). A multi-model assessment of the Global Warming Potential of hydrogen. *Communications Earth & Environment*, *4*(1). https://doi.org/10.1038/s43247-023-00857-8

Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J., Newth, D., Baynes, T., Lenzen, M., & Owen, A. (2016). Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions. *Journal of Cleaner Production*, *132*, 45–56. https://doi.org/10.1016/j.jclepro.2015.06.100

Schenker, V., Kulionis, V., Oberschelp, C., & Pfister, S. (2022). Metals for low-carbon technologies: Environmental impacts and relation to planetary boundaries. *Journal of Cleaner Production*, *372*, 133620. https://doi.org/10.1016/j.jclepro.2022.133620

Schläger, M., Murtazaev, K., Rakhmatuloev, B., Zoriy, P., & Heuel-Fabianek, B. (2016). Radon exhalation of the uranium tailings dump Digmai, Tajikistan. *RAD Association Journal.* Advance online publication. https://doi.org/10.21175/RadJ.2016.03.041

Siderwin. (2020). *Siderwin Project Deliverable D7.4. Environmental life cycle assessment intermediary report*. https://www.siderwin-spire.eu/sites/siderwin.drupal.pulsartecnalia.com/files/documents/D7.4.Environmental%20life%20cycle%20assessment%20intermediary%20report.pdf

Sonter, L. J., Ali, S. H., & Watson, J. E. M. (2018). Mining and biodiversity: Key issues and research needs in conservation science. *Proceedings. Biological Sciences*, *285*(1892). https://doi.org/10.1098/rspb.2018.1926

Sonter, L. J., Herrera, D., Barrett, D. J., Galford, G. L., Moran, C. J., & Soares-Filho, B. S. (2017). Mining drives extensive deforestation in the Brazilian Amazon. *Nature Communications*, *8*(1), 1013. https://doi.org/10.1038/s41467-017-00557-w

Speizer, S., Durga, S., Blahut, N., Charles, M., Lehne, J., Edmonds, J., & Yu, S. (2023). Rapid implementation of mitigation measures can facilitate decarbonization of the global steel sector in 1.5°C-consistent pathways. *One Earth*, *6*(11), 1494–1509. https://doi.org/10.1016/j.oneear.2023.10.016

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., Vries, W. de, Wit, C. A. de, Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Sustainability. Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855. https://doi.org/10.1126/science.1259855

Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, M., & Prins, A. (2014). *Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model description and policy applications.*

Steubing, B., & Koning, D. de (2021). Making the use of scenarios in LCA easier: the superstructure approach. *The International Journal of Life Cycle Assessment*, *26*(11), 2248–2262. https://doi.org/10.1007/s11367-021-01974-2

Steubing, B., Koning, D. de, Haas, A., & Mutel, C. L. (2020). The Activity Browser — An open source LCA software building on top of the brightway framework. *Software Impacts*, *3*, 100012. https://doi.org/10.1016/j.simpa.2019.100012

Steubing, B., Mendoza Beltran, A., & Sacchi, R. (2023). Conditions for the broad application of prospective life cycle inventory databases. *The International Journal of Life Cycle Assessment*, *28*(9), 1092–1103. https://doi.org/10.1007/s11367-023-02192-8

Toktarova, A., Karlsson, I., Rootzén, J., Göransson, L., Odenberger, M., & Johnsson, F. (2020). Pathways for Low-Carbon Transition of the Steel Industry—A Swedish Case Study. *Energies*, *13*(15). https://doi.org/10.3390/en13153840

Tong, D., Zhang, Q [Qiang], Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., & Davis, Steven J %J Nature (2019). Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target, *572*(7769), 373–377.

U.S. Department of Energy. (2016). *Uranium Mining and Milling near Rifle, Colorado*. https://www.energy.gov/lm/articles/uranium-mining-and-milling-near-rifle-colorado

Vadén, T., Lähde, V., Majava, A., Järvensivu, P., Toivanen, T., Hakala, E., & Eronen, J. T. (2020). Decoupling for ecological sustainability: A categorisation and review of research literature. *Environmental Science & Policy*, *112*, 236–244. https://doi.org/10.1016/j.envsci.2020.06.016

van den Oever, A. E., Puricelli, S., Costa, D., Thonemann, N., Lavigne Philippot, M., & Messagie, M. (2024). Revisiting the challenges of ozone depletion in life cycle assessment. *Cleaner Environmental Systems*, *13*, 100196. https://doi.org/10.1016/j.cesys.2024.100196

van der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G. J., & Tukker, A. (2020). A critical view on the current application of LCA for new technologies and recommendations for improved practice. *Journal of Cleaner Production*, *259*, 120904. https://doi.org/10.1016/j.jclepro.2020.120904

van der Voet, E., van Oers, L., Verboon, M., & Kuipers, K. (2019). Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals. *Journal of Industrial Ecology*, *23*(1), 141–155. https://doi.org/10.1111/jiec.12722

van Ruijven, B. J., van Vuuren, D. P., Boskaljon, W., Neelis, M. L., Saygin, D., & Patel, M. K. (2016). Long-term model-based projections of energy use and CO_2 emissions from the

global steel and cement industries. *Resources, Conservation and Recycling*, *112*, 15–36. https://doi.org/10.1016/j.resconrec.2016.04.016
van Sluisveld, M. A., Boer, H. S. de, Daioglou, V., Hof, A. F., & van Vuuren, D. P. (2021). A race to zero - Assessing the position of heavy industry in a global net-zero CO_2 emissions context. *Energy and Climate Change*, *2*, 100051. https://doi.org/10.1016/j.egycc.2021.100051
van Sluisveld, M. A., Harmsen, M. J., van Vuuren, D. P., Bosetti, V., Wilson, C., & van der Zwaan, B. (2018). Comparing future patterns of energy system change in 2 °C scenarios to expert projections. *Global Environmental Change*, *50*, 201–211. https://doi.org/10.1016/j.gloenvcha.2018.03.009
van Sluisveld, M. A., Hof, A. F., Carrara, S., Geels, F. W., Nilsson, M., Rogge, K., Turnheim, B., & van Vuuren, D. P. (2020). Aligning integrated assessment modelling with socio-technical transition insights: An application to low-carbon energy scenario analysis in Europe. *Technological Forecasting and Social Change*, *151*, 119177. https://doi.org/10.1016/j.techfore.2017.10.024
van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., & Rose, S. K. (2011). The representative concentration pathways: an overview. *Climatic Change*, *109*(1-2), 5–31. https://doi.org/10.1007/s10584-011-0148-z
Voldsund, M., Gardarsdottir, S., Lena, E. de, Pérez-Calvo, J.-F., Jamali, A., Berstad, D., Fu, C., Romano, M., Roussanaly, S., Anantharaman, R., Hoppe, H., Sutter, D., Mazzotti, M., Gazzani, M., Cinti, G., & Jordal, K. (2019). Comparison of Technologies for CO_2 Capture from Cement Production—Part 1: Technical Evaluation. *Energies*, *12*(3). https://doi.org/10.3390/en12030559
Volkart, K., Bauer, C., & Boulet, C. (2013). Life cycle assessment of carbon capture and storage in power generation and industry in Europe. *International Journal of Greenhouse Gas Control*, *16*, 91–106. https://doi.org/10.1016/j.ijggc.2013.03.003
Wang, P., Ryberg, M., Yang, Y., Feng, K., Kara, S., Hauschild, M., & Chen, W. Q. (2021). Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. *Nat Commun*, *12*(1), 2066. https://doi.org/10.1038/s41467-021-22245-6
Wang, Y [Yaxin], Liu, J., Tang, X., Wang, Y [Yu], An, H., & Yi, H. (2023). Decarbonization pathways of China's iron and steel industry toward carbon neutrality. *Resources, Conservation and Recycling*, *194*, 106994. https://doi.org/10.1016/j.resconrec.2023.106994
Watari, T., Cabrera Serrenho, A., Gast, L., Cullen, J., & Allwood, J. (2023). Feasible supply of steel and cement within a carbon budget is likely to fall short of expected global demand. *Nature Communications*, *14*(1), 7895. https://doi.org/10.1038/s41467-023-43684-3
Watari, T., & McLellan, B. (2024). Global demand for green hydrogen-based steel: Insights from 28 scenarios. *International Journal of Hydrogen Energy*, *79*, 630–635. https://doi.org/10.1016/j.ijhydene.2024.06.423

Watari, T., Nansai, K., & Nakajima, K. (2021). Major metals demand, supply, and environmental impacts to 2100: A critical review. *Resources, Conservation and Recycling*, *164*, 105107. https://doi.org/10.1016/j.resconrec.2020.105107

Weckenborg, C., Graupner, Y., & Spengler, T. S. (2024). Prospective assessment of transformation pathways toward low-carbon steelmaking: Evaluating economic and climate impacts in Germany. *Resources, Conservation and Recycling*, *203*, 107434. https://doi.org/10.1016/j.resconrec.2024.107434

Wei, S., Sacchi, R., Tukker, A., Suh, S., & Steubing, B. (2024). Future environmental impacts of global hydrogen production. *Energy & Environmental Science*, *17*(6), 2157–2172. https://doi.org/10.1039/D3EE03875K

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

WHO. (2021). *Global Air Quality Guidelines.: Particulate Matter (PM2. 5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. World Health Organization*. https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=30479186

Xu, R., Tong, D., Davis, S. J., Qin, X., Cheng, J., Shi, Q., Liu, Y., Chen, C., Yan, L., Yan, X., Wang, H., Zheng, D., He, K., & Zhang, Q [Qiang] (2023). Plant-by-plant decarbonization strategies for the global steel industry. *Nature Climate Change*, *13*(10), 1067–1074. https://doi.org/10.1038/s41558-023-01808-z

Yang, L., Wang, X.-C., Dai, M., Chen, B., Qiao, Y., Deng, H., Zhang, D., Zhang, Y., Villas Bôas de Almeida, C. M., Chiu, A. S., Klemeš, J. J., & Wang, Y [Yutao] (2021). Shifting from fossil-based economy to bio-based economy: Status quo, challenges, and prospects. *Energy*, *228*, 120533. https://doi.org/10.1016/j.energy.2021.120533

Yokoi, R., Watari, T., & Motoshita, M. (2022). Future greenhouse gas emissions from metal production: gaps and opportunities towards climate goals. *Energy & Environmental Science*, *15*(1), 146–157. https://doi.org/10.1039/d1ee02165f

Yuan, B., Kongstein, O. E., & Haarberg, G. M. (2009). Electrowinning of iron in aqueous alkaline solution using a rotating cathode. *Journal of the Electrochemical Society*, *156*(2), D64. https://doi.org/10.1149/1.3039998

Zhang, X., Jiao, K., Zhang, J., & Guo, Z. (2021). A review on low carbon emissions projects of steel industry in the World. *Journal of Cleaner Production.* Advance online publication. https://doi.org/10.1016/j.jclepro.2021.127259

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.

References

Cox, B., Mutel, C. L., Bauer, C., Mendoza Beltran, A., & van Vuuren, D. P. (2018). Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles. *Environ Sci Technol*, *52*(8), 4989–4995. https://doi.org/10.1021/acs.est.8b00261

Creutzig, F., Simoes, S. G., Leipold, S., Berrill, P., Azevedo, I., Edelenbosch, O., Fishman, T., Haberl, H., Hertwich, E., Krey, V., Lima, A. T., Makov, T., Mastrucci, A., Milojevic-Dupont, N., Nachtigall, F., Pauliuk, S., Silva, M., Verdolini, E., van Vuuren, D., . . . Wilson, C. (2024). Demand-side strategies key for mitigating material impacts of energy

transitions. *Nature Climate Change*, *14*(6), 561–572. https://doi.org/10.1038/s41558-024-02016-z
European Commission (2025). The Clean Industrial Deal: A joint roadmap for competitiveness and decarbonisation.
Giljum, S., Maus, V., Sonter, L., Luckeneder, S., Werner, T., Lutter, S., Gershenzon, J., Cole, M. J., Siqueira-Gay, J., & Bebbington, A. (2025). Metal mining is a global driver of environmental change. *Nature Reviews Earth & Environment.* Advance online publication. https://doi.org/10.1038/s43017-025-00683-w
Harpprecht, C., Naegler, T., Steubing, B., Tukker, A., & Simon, S. (2022). Decarbonization scenarios for the iron and steel industry in context of a sectoral carbon budget: Germany as a case study. *Journal of Cleaner Production*, *380*, 134846. https://doi.org/10.1016/j.jclepro.2022.134846
Hellweg, S., Benetto, E., Huijbregts, M. A. J., Verones, F., & Wood, R. (2023). Life-cycle assessment to guide solutions for the triple planetary crisis. *Nature Reviews Earth & Environment*, *4*(7), 471–486. https://doi.org/10.1038/s43017-023-00449-2
Hertwich, E. G., Ali, S., Ciacci, L., Fishman, T., Heeren, N., Masanet, E., Asghari, F. N., Olivetti, E., Pauliuk, S., Tu, Q., & Wolfram, P. (2019). Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. *Environmental Research Letters*, *14*(4), 43004. https://doi.org/10.1088/1748-9326/ab0fe3
IRENA. (2023). *Geopolitics of the energy transition: critical materials. Abu Dhabi: IRENA, International Renewable Energy Agency.*
IRP. (2019). *Global Resources Outlook 2019: Natural Resources for the Future We Want*. A Report of the International Resource Panel. United Nations Environment Programme. United Nations Environment Programme. https://www.un-ilibrary.org/content/books/9789280737417 https://doi.org/10.18356/689a1a17-en
IRP. (2020). *Mineral Resource Governance in the 21st Century: Gearing Extractive Industries Towards Sustainable Development.* A Report by the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya. https://www.un-ilibrary.org/content/books/9789280737790 https://doi.org/10.18356/d4ca45f2-en
Mendoza Beltran, A., Cox, B., Mutel, C., Vuuren, D. P., Font Vivanco, D., Deetman, S., Edelenbosch, O. Y., Guinée, J., & Tukker, A. (2018). When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment. *Journal of Industrial Ecology*, *24*(1), 64–79. https://doi.org/10.1111/jiec.12825
Mengis, N., Kalhori, A., Simon, S., Harpprecht, C., Baetcke, L., Prats, E., Schmidt-Hattenberger, C., Stevenson, A., Dold, C., El Zohbi, J., Borchers, M., Thrän, D., Korte, K., Gawel, E., Dolch, T., Heß, D., Yeates, C., Thoni, T., Markus, T., . . . Dittmeyer, R. (2022). Net-zero CO2 Germany - A retrospect from the year 2050. *Earth's Future.* Advance online publication. https://doi.org/10.1029/2021ef002324
Milford, R. L., Pauliuk, S., Allwood, J. M., & Müller, D. B. (2013). The roles of energy and material efficiency in meeting steel industry CO2 targets. *Environmental Science & Technology*, *47*(7), 3455–3462. https://doi.org/10.1021/es3031424
Müller, A., Harpprecht, C., Sacchi, R., Maes, B., van Sluisveld, M., Daioglou, V., Šavija, B., & Steubing, B. (2024). Decarbonizing the cement industry: Findings from coupling

prospective life cycle assessment of clinker with integrated assessment model scenarios. *Journal of Cleaner Production*, *450*, 141884. https://doi.org/10.1016/j.jclepro.2024.141884
Nijnens, J., Behrens, P., Kraan, O., Sprecher, B., & Kleijn, R. (2023). Energy transition will require substantially less mining than the current fossil system. *Joule*, *7*(11), 2408–2413. https://doi.org/10.1016/j.joule.2023.10.005
Nuss, P., & Eckelman, M. J. (2014). Life cycle assessment of metals: a scientific synthesis. *PloS One*, *9*(7), e101298.
Pizzol, M., Laurent, A., Sala, S., Weidema, B., Verones, F., & Koffler, C. (2017). Normalisation and weighting in life cycle assessment: quo vadis? *The International Journal of Life Cycle Assessment*, *22*(6), 853–866. https://doi.org/10.1007/s11367-016-1199-1
Sacchi, R., Terlouw, T., Dirnauchner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., & Luderer, G. (2021). PRospective EnvironMental Impact asSEment (premise): a streamlined approach to producing databases for prospective Life Cycle Assessment using Integrated Assessment Models. *Renewable and Sustainable Energy Reviews.* Advance online publication. https://doi.org/10.1016/j.rser.2022.112311
Schenker, V., Kulionis, V., Oberschelp, C., & Pfister, S. (2022). Metals for low-carbon technologies: Environmental impacts and relation to planetary boundaries. *Journal of Cleaner Production*, *372*, 133620. https://doi.org/10.1016/j.jclepro.2022.133620
Schlichenmaier, S., & Naegler, T. (2022). May material bottlenecks hamper the global energy transition towards the 1.5 °C target? *Energy Reports*, *8*, 14875–14887. https://doi.org/10.1016/j.egyr.2022.11.025
Sonter, L. J., Ali, S. H., & Watson, J. E. M. (2018). Mining and biodiversity: Key issues and research needs in conservation science. *Proceedings. Biological Sciences*, *285*(1892). https://doi.org/10.1098/rspb.2018.1926
Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., Vries, W. de, Wit, C. A. de, Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Sustainability. Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855. https://doi.org/10.1126/science.1259855
Terlouw, T., Treyer, K., Bauer, C., & Mazzotti, M. (2021). Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources. *Environmental Science & Technology*, *55*(16), 11397–11411. https://doi.org/10.1021/acs.est.1c03263
Troll, V. R., & Arndt, N. T. (2022). European Raw Materials Resilience—Turning a Blind Eye. *Earth Science, Systems and Society*, *2*(1), Article 10058. https://doi.org/10.3389/esss.2022.10058
UNDP. (2016). *White paper. Mapping Mining to the Sustainable Development Goals: An Atlas. United Nations Development Programme.*
van der Voet, E., van Oers, L., Verboon, M., & Kuipers, K. (2019). Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals. *Journal of Industrial Ecology*, *23*(1), 141–155. https://doi.org/10.1111/jiec.12722

Wang, P., Ryberg, M., Yang, Y., Feng, K., Kara, S., Hauschild, M., & Chen, W. Q. (2021). Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. *Nat Commun*, *12*(1), 2066. https://doi.org/10.1038/s41467-021-22245-6

Watari, T., Cabrera Serrenho, A., Gast, L., Cullen, J., & Allwood, J. (2023). Feasible supply of steel and cement within a carbon budget is likely to fall short of expected global demand. *Nature Communications*, *14*(1), 7895. https://doi.org/10.1038/s41467-023-43684-3

Watari, T., & McLellan, B. (2024). Global demand for green hydrogen-based steel: Insights from 28 scenarios. *International Journal of Hydrogen Energy*, *79*, 630–635. https://doi.org/10.1016/j.ijhydene.2024.06.423

Watari, T., Nansai, K., & Nakajima, K. (2020). Review of critical metal dynamics to 2050 for 48 elements. *Resources, Conservation and Recycling*, *155*, 104669. https://doi.org/10.1016/j.resconrec.2019.104669

Watari, T., Nansai, K., & Nakajima, K. (2021). Major metals demand, supply, and environmental impacts to 2100: A critical review. *Resources, Conservation and Recycling*, *164*, 105107. https://doi.org/10.1016/j.resconrec.2020.105107

Wei, S., Sacchi, R., Tukker, A., Suh, S., & Steubing, B. (2024). Future environmental impacts of global hydrogen production. *Energy & Environmental Science*, *17*(6), 2157–2172. https://doi.org/10.1039/D3EE03875K

Yokoi, R., Watari, T., & Motoshita, M. (2022). Future greenhouse gas emissions from metal production: gaps and opportunities towards climate goals. *Energy & Environmental Science*, *15*(1), 146–157. https://doi.org/10.1039/d1ee02165f

Zhong, X., Hu, M., Deetman, S., Steubing, B., Lin, H. X., Hernandez, G. A., Harpprecht, C., Zhang, C., Tukker, A., & Behrens, P. (2021). Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060. *Nature Communications*, *12*(1), 1–10. https://doi.org/10.1038/s41467-021-26212-z

Acknowledgements

This work would have not been possible without the support of my supervisors, colleagues, collaborators, friends and family.

I had the great privilege of working with very experienced, understanding and supportive supervisors who created an open and warm environment for meetings or discussions, which I highly appreciated. First, I would like to thank my supervisors from DLR, Dr. Tobias Naegler and Dr. Sonja Simon, who provided invaluable support and guidance. Your patience, willingness to listen and reflect, and especially extra-ordinary kindness provided not only indispensable advice but also an open-hearted collaboration even in challenging times. I am also deeply grateful to my supervisors at Leiden University (CML), Dr. Bernhard Steubing and Prof. Dr. Arnold Tukker, who offered warm-hearted support, thoughtful guidance and valuable advice whenever needed.

My gratitude extends to all collaborators and co-authors. Starting with the Paul Scherer Institute, who hosted me for a research stay abroad. Thank you, Dr. Romain Sacchi and Christian Bauer, for making this experience possible. Special thanks to Romain for your contribution to our steel project and its integration in *premise*.

I would like to thank my fellow PhD colleagues at CML, Brenda Miranda Xicotentacl, Sander van Nielen, Marc van der Meide, Chen Li, and Zhijie Li, for making our joint review project a refreshing and fun experience.

My gratitude further extends to Dr. Mariësse van Sluisveld, Dr. Vassilis Daioglou, Dr. Lauran van Oers, and Dr. Stephen Northey, for insightful discussions and your valuable contributions, as well as to Dr. Benjamin Fuchs from DLR for his technical support and help in coding-related questions.

Further, I would like to thank fellow PhD candidates and friends at DLR and CML, for their support, enriching conversations, sharing experiences, and for offering help or fun distractions during coffee breaks and after work.

Lastly, I am extremely grateful for all the unconditional support, patience, confidence, and love I have been fortunate to receive from my family, dear friends, partner, and housemates. First and foremost, I wish to thank my mum, followed by my sister, Julius, and Olga-Milena, as well as Mira, Anna, Meli, Stani, Sveni, Gigi, Sabrina, Michael, Marie, Sofie, Diego, Camila, friends from beachvolleyball and the FranzWerk in Tübingen, among others. Altogether, you accompanied me throughout these years, and it is due to you and all the joy, trust, and love you brought into my life that I finalized this thesis. Finally, I would like to thank my dear grandmother Zita, whose big heart, courage and strength, I have always admired.

Curriculum Vitae

Carina Harpprecht was born on November 24th, 1991, in Esslingen am Neckar, Germany.

After completing her secondary education at the Heinrich-Heine-Gymnasium in Ostfildern (Germany) in 2011, she received a Bachelor of Science degree in *Engineering Science* from the University of Bayreuth (Germany) in 2016. She then graduated with distinction *'summa cum laude'* from the joint Master's program in *Industrial Ecology* offered by Leiden University (LU) and TU Delft in 2019.

In 2020, Carina started a Ph.D. at the *Institute of Networked Energy Systems* at the German Aerospace Center (DLR) in collaboration with the *Institute of Environmental Science* (CML) at Leiden University (LU). Her research focuses on the assessment of the future environmental impacts of metal production and energy-intensive sectors with a methodological emphasis on a consistent combination of scenarios from multiple sectors, e.g., considering the energy transition. During a three-month research stay at the Paul Scherrer Institute (PSI) in Switzerland in 2021, she began the project on decarbonization scenarios for global steel production using Integrated Assessment Models, a collaboration with PSI. As a research assistant at DLR, Carina furthermore worked on the development of scientific software enabling a transparent and reproducible environmental impact assessment of energy scenarios from energy system models.

The Ph.D. research was supervised by Dr. Tobias Naegler (DLR), Dr. Bernhard Steubing (LU) and Prof. Dr. Arnold Tukker (LU).

List of Publications

Peer-reviewed publications

Harpprecht, C., Sacchi, R., Naegler, T., Van Sluisveld, M., Daioglou, V., Tukker, A., Steubing, B. (2025). Future environmental impacts of global iron and steel production. *Energy & Environmental Science.* https://doi.org/10.1039/D5EE01356A

Harpprecht, C., Miranda Xicotencatl, B., van Nielen, S., van der Meide, M., Li, C., Li, Z., Tukker, A., Steubing, B. (2024). Future environmental impacts of metals: a systematic review of impact trends, modelling approaches, and challenges. *Resources, Conservation & Recycling, 205,* 107572. https://doi.org/10.1016/j.resconrec.2024.107572

Harpprecht, C., Naegler, T., Steubing, B., Tukker, A., & Simon, S. (2022). Decarbonization scenarios for the iron and steel industry in context of a sectoral carbon budget: Germany as a case study. *Journal of Cleaner Production*, *380*, 134846. https://doi.org/10.1016/j.jclepro.2022.134846

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

Terlouw, T., Moretti, C., **Harpprecht, C.**, Sacchi, R., McKenna, R. & Bauer, C. (2025). Global greenhouse gas emissions mitigation potential of existing and planned hydrogen projects. *Nature Energy.* https://doi.org/10.1038/s41560-025-01892-9

Müller, A., **Harpprecht, C.,** Sacchi, R., Maes, B., Van Sluisveld, M., Daioglou, V., Šavija, B., Steubing, B. (2024). Decarbonizing the cement industry: Findings from coupling Life Cycle Assessment of Clinker with Integrated Assessment Model Scenarios. *Journal of Cleaner Production.* https://doi.org/10.1016/j.jclepro.2024.141884

Mengis, N., Kalhori, A., Simon, S., **Harpprecht, C.,** Baetcke, L., Prats-Salvado, E., ... & Dittmeyer, R. (2022). Net-zero CO_2 Germany—A retrospect from the year 2050. *Earth's Future*, *10*(2). https://doi.org/10.1029/2021EF002324

Xu, C., Steubing, B., Hu, M., **Harpprecht, C.,** van der Meide, M., & Tukker, A. (2022). Future greenhouse gas emissions of automotive lithium-ion battery cell production. *Resources, Conservation and Recycling*, *187*, 106606. https://doi.org/10.1016/j.resconrec.2022.106606

van der Meide, M., **Harpprecht, C.,** Northey, S., Yang, Y., & Steubing, B. (2022). Effects of the energy transition on environmental impacts of cobalt supply: A prospective life cycle assessment study on future supply of cobalt. *Journal of Industrial Ecology*, *26*(5), 1631-1645. https://doi.org/10.1111/jiec.13258

Simon, S., Xiao, M., **Harpprecht, C.,** Sasanpour, S., Gardian, H., & Pregger, T. (2022). A pathway for the German energy sector compatible with a 1.5° C carbon budget. *Sustainability*, *14*(2), 1025. https://doi.org/10.3390/su14021025

Zhong, X., Hu, M., Deetman, S., Steubing, B., Lin, H. X., Hernandez, G. A., **Harpprecht, C.,** Zhang, C., Tukker, A. & Behrens, P. (2021). Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060. *Nature Communications*, *12*(1), 6126. https://doi.org/10.1038/s41467-021-26212-z

Open-source and data publications

Harpprecht, C., Sacchi, R., Naegler, T., van Sluisveld, M., Daioglou, V., Arnold, T., & Steubing, B. (2025). Code and data for publication: Future Environmental Impacts of Global Iron and Steel Production. *Zenodo*. https://doi.org/10.5281/zenodo.14968094

Harpprecht, C., & Fuchs, B. (2024). bw_superstructure python library (1.0.1). *Zenodo*. https://doi.org/10.5281/zenodo.11199476; https://github.com/dlr-ve-esy/bw_superstructure

Harpprecht, C., Miranda Xicotencatl, B., van Nielen, S., van der Meide, M., Li, C., Li, Z., Tukker, A., & Steubing, B. (2023). Supplementary data for the article: Future environmental impacts of metals: a systematic review of impact trends, modelling approaches, and challenges [Data set]. *Zenodo*. https://doi.org/10.5281/zenodo.10066584

Harpprecht, C., Naegler, T., Steubing, B., Tukker, A., & Simon, S. (2022). 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. *Zenodo*. https://doi.org/10.5281/zenodo.7305509

Harpprecht, C., van Oers, L., Northey, S. A., Yang, Y., & Steubing, B. (2022). Scenario data for article: Environmental impacts of key metals' supply and low-carbon technologies are likely to decrease in the future*. Zenodo.* https://doi.org/10.5281/zenodo.6108047

Müller, A., **Harpprecht, C.**, Sacchi, R., Maes, B., van Sluisveld, M., Daioglou, V., Šavija, B., & Steubing, B. (2023). Code and data for publication: Decarbonizing the cement industry: Findings from coupling prospective life cycle assessment of clinker with integrated assessment model scenarios. *Zenodo*. https://doi.org/10.5281/zenodo.10255594

Simon, S., Xiao, M., **Harpprecht, C.**, Sasanpour, S., Gardian, H., & Pregger, T. (2021). Comprehensive result data for a pathway for the German energy sector compatible with a 1.5°C carbon budget [Data set]. *Zenodo*. https://doi.org/10.5281/zenodo.5761840

Annex

A Supplementary material for Chapters 2-5

Table A.1: Links to supplementary materials available online for each chapter.

Chapter	Supplementary material
2	https://ars.els-cdn.com/content/image/1-s2.0-S0921344924001678-mmc1.pdf
3	https://doi.org/10.1111/jiec.13181
4	https://www.sciencedirect.com/science/article/pii/S0959652622044195#appsec1
5	https://www.rsc.org/suppdata/d5/ee/d5ee01356a/d5ee01356a1.pdf

B Sensitivity analyses for Chapters 4 and 5

Simplified sensitivity analyses for alternative steel demand scenarios for Chapters 4 and 5 assess the effect of lower steel production amounts in Germany (Chapter 4) and globally (Chapter 5).

Assumptions

The steel production amounts are reduced as follows.

- For the German steel scenarios (Chapter 4), instead of a constant production of 42.4 Mt steel/year, steel production linearly declines from 2020 onwards such that it reaches a 30% reduction by 2050 compared to 2020 (29.68 Mt steel/year). This represents an annual reduction rate of 1% of the 2020 production levels, i.e., 0.424 Mt steel/year.
- For the global steel study (Chapter 5), the sensitivity analysis assumes constant steel production instead of an increase by 61% from 2020 by 2060.

For emission intensities, the original trajectories of the steel production market mixes are assumed as proxies. These are presented in Figure 5 (Chapter 4) and in Figure 6 (Chapter 5) for the German and the global study, respectively.

Results

When assuming these reduced demand scenarios of the sensitivity analysis, the steel industry may still consume disproportionately large shares of the remaining carbon budgets in the future.

For Germany, the resulting cumulative CO_2 emissions are reduced by 10-14% compared to the respective original scenarios by 2050 (see Figure B.1), i.e., by 86-210 Mt CO_2. Nevertheless, they exceed the proportional share of the 1.5°C and 1.75°C carbon budgets allocated for the German steel industry in this study. Only the very best-performing CCS scenario nearly meets the upper boundary of the proportional 1.75°C budget with an overshoot of 2% by 2050. The decarbonization scenarios still require 9-12% and 8-11% of the upper thresholds of the proportional 1.5°C and 1.75°C budgets, respectively. These shares are much higher when assuming less beneficial distribution approaches for defining German carbon budgets (see Table 5, Chapter 4), representing the lower boundaries of the carbon budgets.

For the global steel scenarios, cumulative emissions are reduced by 21% and 18% for the 2°C and 1.5°C scenario respectively, i.e., by 26 and 16 Gt CO_2-eq. They represent 7-11% and 15-24% of the 2°C and 1.5°C budgets by 2060 respectively (assuming the 50th-83th percentile of the carbon budgets). As such, they may meet their proportionate share of the global end-of-the-century 2°C budget by 2060, but still clearly exceed their share of the 1.5°C budget.

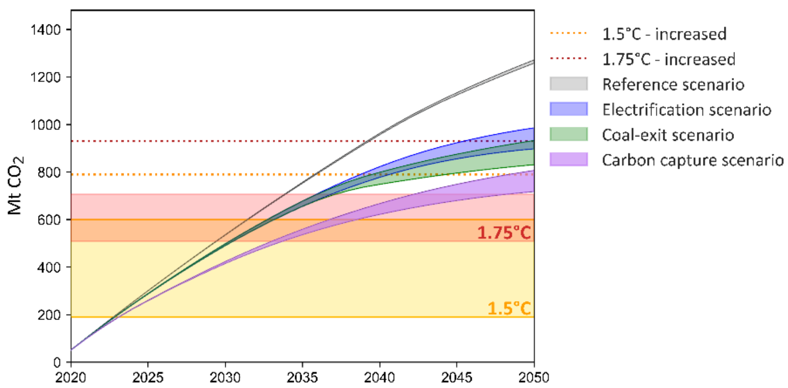


Figure B.1: Results of the sensitivity analysis assuming a linear decline of steel production in Germany reaching -30% by 2050 compared to 2020. Cumulative CO_2 emissions for 2020-2050 per scenario compared to proportional carbon budgets of the iron and steel industry in Germany for a 1.5°C (yellow area, average share) and a 1.75°C (red area, average share) climate target (for budget definition see Table 6, Chapter 4). The dashed horizontal lines represent the carbon budgets if the allocation share for the steel industry is increased from its average of 7.6% to 10%. For each scenario, the emission factor of electricity is varied between minimum and maximum values (see Table 4, Chapter 4). Results for the original scenarios with constant production amounts are provided in Figure 6, in Chapter 4.

Reflections

Although cumulative emissions to some extent reach levels very close to the carbon budgets by 2050 and 2060 under the assumed decreased production amounts, the results should be interpreted with caution. Cumulative emissions will very likely continue to rise by the end of the century requiring additional shares of the carbon budgets, as steel production is unlikely to be climate-neutral by 2060 (Figure 6, Chapter 5). Consequently, meeting the carbon budgets by 2100 is less feasible than by 2060. Furthermore, the assumptions of demand reductions are substantial, i.e., a 30% decrease within 30 years, and constant instead of a 61% increase within 40 years. Achieving such drastic demand changes poses a considerable challenge.

Nevertheless, demand is a direct multiplier of emissions. As such, reducing demand represents a very effective mitigation strategy, particularly in the near future, when emission intensities are still high, and under scenarios with less ambitious climate targets.

It is important to note that these sensitivity analyses estimate the effect of lowering production amounts but they do not represent consistent supply and demand scenarios generated by IMAGE, since emission intensities are based on the original production scenarios instead of derived from new supply scenarios. Hence, emission intensities and cumulative emissions may be overestimated in this analysis, as, for example, secondary production shares may be higher and primary production lower under decreased production amounts. Hence, the sensitivity analysis represents a conservative estimate.

Analyses which can consistently couple comprehensive demand and supply scenarios require methods and models which are beyond the scope of this work, and are thus subject for future research.