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

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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

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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

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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

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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.

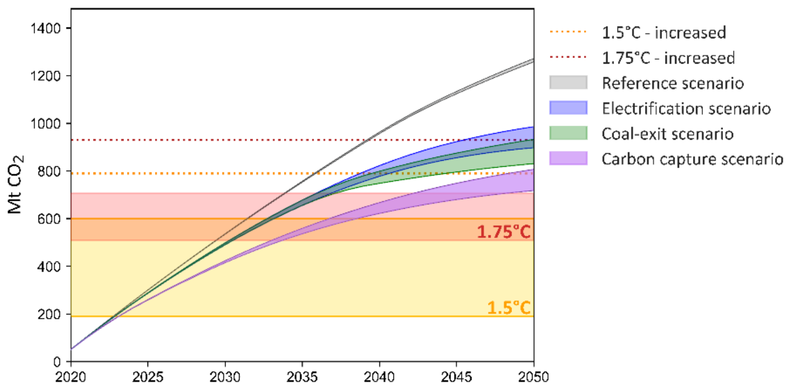

Figure B.1: Results of the sensitivity analysis assuming a linear decline of steel production in Germany reaching -30% by 2050 compared to 2020. Cumulative CO_2 emissions for 2020-2050 per scenario compared to proportional carbon budgets of the iron and steel industry in Germany for a 1.5°C (yellow area, 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.