



Life cycle assessment of natural gas based steelmaking via the direct reduction – Electric Arc Furnace route

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Received: 15 December 2025 / Accepted: 10 April 2026
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Abstract

Purpose To decarbonize steel production, many European steelmakers are actively transitioning towards the Direct Reduction – Electric Arc Furnace (DR-EAF) route. Therefore, the purpose of this paper was to conduct a Life Cycle Assessment (LCA) on the DR-EAF route across multiple impact categories. The relative significance of impact categories and trade-offs to Blast Furnace – Basic Oxygen Furnace (BF-BOF) steelmaking were identified. Finally, the influence of different burden compositions on the LCA results was analyzed.

Methods This paper conducted a literature review on the state of environmental assessments of DR-EAF steelmaking, in addition to developing a Life Cycle Assessment (LCA) for a theoretical site operated in Germany. The LCA was conducted using CML 2001 v. 2016 and the software LCA for Experts. An inventory has been developed for the direct reduction plant, EAF, and continuous casting. Background data was modelled using the Sphera database. A flexible input/output model was developed to represent the EAF, with which three scenarios were investigated, considering different furnace charges.

Results The literature review found that, while many environmental assessments have been conducted on this steel production route, most studies focus on Global Warming Potential (GWP100). Few authors assess multiple impact categories or the relative significance of different environmental impacts for the assessed product systems. The LCA identified environmental hotspots in the production of ore based metallics, electricity, and the defined alloy mix. Through normalization, Abiotic Depletion Potential for Fossil fuels (ADP-F), Acidification Potential (AP), GWP100 and Photochemical Ozone Creation Potential (POCP) have been identified as relevant environmental impact categories for both DR-EAF as well as BF-BOF steelmaking. Compared to the BF-BOF route, a singular trade-off is observed for DR-EAF based steel production for ADP-F. This trade-off can be negated should renewable electricity be used during production.

Conclusions Overall, the DR-EAF route has the potential to lead to improvements in environmental performance across all of the relevant impact categories, when renewable electricity is utilized. It is recommended that future research focus on a more in depth comparison of the DR-EAF and BF-BOF routes, in addition to addressing comparability issues brought on by the assessment of steel scrap using the cut-off method.

Keywords Life Cycle Assessment · Direct reduction plant · Electric Arc Furnace · Sustainability · Steel · Steelmaking

Communicated by: Edrzej Kasprzak

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1 Introduction

As the effects of climate change are felt worldwide, an increased awareness of environmental issues is growing amongst the general public (Leiserowitz et al. 2021; UBA 2025). The demand for sustainable products and services is increasing, with both industries and nations alike setting ambitious targets to improve environmental aspects of their products, services, and policies (Paris Agreement, 2016; SBTi, 2023). Within this context, steel is a vital raw material for industries such as automotive, or construction (EUROFER, 2025). In response to growing global demand, 71% of steel produced in 2024 was manufactured through primary steelmaking via the Blast Furnace–Basic Oxygen Furnace (BF-BOF) route (WSA, 2024). According to the World Steel Association (WSA), BF-BOF steelmaking is tied to an average emission intensity of 2.3 t CO₂ /t Crude Steel (CS), and is one of the main reasons why steel production accounts for 7–9% of global CO₂ emissions annually (WSA, 2024). In Europe, Germany stands out, responsible for 29% of European CS, 72% of which is produced via the BF-BOF route (EUROFER, 2025; WV Stahl, 2023). This underlines the need for decarbonization within the industry, especially in major producing countries.

In this context, a promising technology configuration is the so called Direct Reduction – Electric Arc Furnace (DR-EAF) route. Direct Reduced Iron (DRI), and steel scrap are melted and refined in an Electric Arc Furnace (EAF) to produce steel. The specific ratio of input materials depends on a number of technical and economic factors, such as scrap availability and chemical impurities (Madias 2014; Raabe et al. 2024). DRI is produced in the solid state within a Direct Reduction Plant (DRP), mainly using continuously operating shaft furnaces (Midrex Technologies, Inc. 2024a). Iron ore pellets are charged at the top of the shaft furnace, and a reducing gas is entered in the middle segment of the shaft. As the pellets move through the furnace, they are reduced in counter flow. The reducing gas, consisting mainly of carbon monoxide and hydrogen, is produced from natural gas either through catalytic, or in situ reforming (Ichikawa et al. 2015; Midrex Technologies, Inc. 2018a; Tenova S.p.A. 2020). Alternative gas sources, such as coke oven gas, or coal gasification gas can also be used (Midrex Technologies, Inc., 2014). DRI produced in a stand-alone DRP is cooled in the lower portions of the shaft to prevent reoxidation, and/or briquetted into Hot Briquetted Iron (HBI) to reduce its reactivity (IIMA, 2022; Midrex Technologies, Inc. 2018b). Alternatively, for facilities that include an onsite EAF, the DRI can be charged into the furnace “hot”, increasing EAF productivity and efficiency (Midrex Technologies, Inc. 2018b). Considering the DR-EAF route operated with natural gas, the WSA reports an average CO₂ intensity of 1.4 t

CO₂ /t CS (WSA, 2024). Compared to the BF-BOF route this corresponds to a reduction of 41%. In the long term, the DR-EAF route can be operated exclusively using green hydrogen (Liu et al. 2021). Under such conditions, substantial emission savings are expected. For example, Suer et al. report a Global Warming Potential with a time horizon of 100 years (GWP100) of 0.75 t CO₂ eq./t CS (Suer, Traverso, et al. 2022a). The decarbonization potential of the DR-EAF route is widely recognized among European steel producers, with seven major DR-EAF projects being planned to go into operation before 2030 (Blastr Green Steel, n.d.; EC 2023; Haskoning Nederland B.V. & Tata steel Nederland BV 2025; Hydnum Steel, 2024; Midrex Technologies, Inc. 2024b; Millennium Steel 2024; Saarlust 2024; Salzgitter AG n.d., 2023; Stegra 2025). Two of these projects are situated in Germany, with a combined annual capacity of 4.1 Mt DRI/a (Saarlust 2024; Salzgitter AG n.d., 2023). This number increases to 6.6 Mt DRI/a, if the decarbonization strategy of thyssenkrupp Steel Europe is included, which adopts a slightly different process configuration with a DRP coupled with integrated smelting units (thyssenkrupp Steel Europe AG, 2025). A more detailed overview of individual projects and plant capacities is provided in the supplementary material.

The shift from BF-BOF steelmaking will be gradual, particularly at large sites operating multiple blast furnaces. Decarbonization will likely occur in phases, replacing individual furnaces separately to maintain production capacity (Salzgitter AG n.d.; thyssenkrupp Steel Europe AG, 2025). During this transitional period, other Ore based Metallics (OBM), such as hot metal or pig iron from the blast furnace could also be incorporated in the EAF, enabling more flexible operation (Mühlböck et al. 2026). In general, key process parameters of the EAF, such as required fluxing materials, electricity consumption and produced slag quantities depend on the charged input material (Barati 2010; Kirschen et al. 2011; Tian et al. 2022). As a result, different burden compositions affect the environmental impacts of the DR-EAF route, as a whole. However, as the goal is to decarbonize, much of the sustainability research on this route focusses on GWP100, or CO₂ emissions (Graupner et al. 2023; Nduagu et al. 2022; Rechberger et al. 2020; Suer, Ahrenhold, et al. 2022; Suer, Traverso, et al. 2022a; Vogl et al. 2018; Xue et al. 2024; Zang et al. 2023). Nevertheless, improvements in GWP100 could introduce trade-offs in other environmental indicators, which should be investigated. Therefore, it is crucial to determine the environmental hotspots of DR-EAF steelmaking in a holistic manner.

Within this context, the Life Cycle Assessment (LCA) methodology provides a systematic assessment framework, that allows for the determination of environmental impacts that arise from a product or service over the course of its

entire life cycle. The LCA methodology has been standardized in the International Organization for Standardization (ISO) norms 14040, and 14044, and consists of four iterative phases: the definition of goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpretation of results (DIN 2020a, b). The information generated by an LCA study can be used for process optimization, strategic planning, political decision making as well as informative purposes (DIN 2020a, b). The results of an LCA can be normalized by dividing the impact of the studied product system by the impact of a reference value, otherwise referred to as the normalization reference (DIN 2020b; Hélias and Servien 2021). LCA normalization is useful for interpretive purposes, particularly in identifying the relative significance of impact categories for the studied product system (DIN 2020b). The normalization reference can be either internal, e.g., product variations defined within the same LCA, or external, such as the environmental impact of an economic region in a certain year (Hélias and Servien 2021; Pizzol et al. 2017). External normalization factors are more commonly applied in LCA, with standardized sets being offered as part of impact assessment methods (Benini et al. 2014; Pizzol et al. 2017). This improves the genericity and reproducibility of results (Hélias and Servien 2021; Pizzol et al. 2017).

The goal of this paper is to conduct an LCA on a theoretical DR-EAF plant configuration operated in Germany, thereby investigating multiple impact categories. A key focus is the identification of relevant non-GWP100 impact categories for the DR-EAF route through LCA normalization, and to identify trade-offs to BF-BOF steelmaking. To investigate the influence of burden composition on the LCA results, three charge scenarios are investigated. The remainder of this paper is structured as follows: the literature review section presents an overview of the state-of-the-art on LCA and environmental assessment studies considering the DR-EAF route. In the methodology section, the goal and scope of the LCA is defined, and the LCI analysis is introduced. In the results and discussion section, the LCIA is presented and discussed. Finally, the major findings of the study are summarized in the conclusions, and recommendations for future research are suggested.

2 Literature review

A literature review has been conducted to see to what extent environmental assessments on the DR-EAF route have been published in the past. Multiple online databases were searched, these include: Wiley Online Library, Scopus, ScienceDirect, and Google Scholar. The search was restricted to publications in the English language from January 2018

to February 2025. Titles, abstracts and keywords were searched, using the search terms, synonyms and operators defined in the supplementary material.

In total, 31 publications were found, of which 14 were duplicate entries. This resulted in an initial selection of 17 publications. Content screening was conducted to determine if an environmental assessment on the DR-EAF process configuration had been performed. Three additional publications were discovered during content screening. Although the review primarily examined LCA studies, it also incorporated other publications that address process specific environmental aspects, such as direct emissions, within a broader assessment. Publications focusing on the production of DRI in shaft furnaces have been included as well. In total, four publications were deemed out of scope. Two publications were excluded as they considered only BF-BOF or scrap based EAF production processes, and did not investigate the DR-EAF route. Two publications were excluded as they were not LCAs or other types of process specific environmental assessments. The remaining publications have been summarized in Table 1.

Since 2018, 16 research papers have been published considering the environmental impacts of the DR-EAF route. Of these publications, 12 conducted an LCA, whereas the remaining four consider other process specific environmental assessments. Regarding the 12 identified LCA studies, a few methodological discrepancies have been determined. Most LCA publications fail to specify what type of end-of-life allocation is considered within their study (Li et al. 2021; Nduagu et al. 2022; Ramezani Moziraji et al. 2023, 2024; Taji Eshkaftaki et al. 2024; Zang et al. 2023). Only six articles define this aspect, all of which use the cut-off method (Azimi and van der Spek 2025; Graupner et al. 2023; Huang et al. 2024; Nurdiawati et al. 2023; Suer, Ahrenhold, et al. 2022; Suer, Traverso, et al. 2022a). This corresponds to the findings of previous research, which found that end-of-life allocation is most commonly not defined in steel related LCAs, with the cut-off method being the most prevalent in studies that do (Suer, Traverso, et al. 2022b). Under the cut-off method, steel scrap enters the product system burden free. This significantly influences the results of the impact assessment, and hampers a direct comparison between publications that consider a different scrap charge in the EAF. There appears to be little harmonization on the characterization models used across the analyzed publications. CML 2001 appears most prevalent for quantifying impacts at midpoint level, with 42% of studies using this assessment method (Huang et al. 2024; Li et al. 2021; Suer, Ahrenhold, et al. 2022; Suer, Traverso, et al. 2022a; Taji Eshkaftaki et al. 2024). Nevertheless, other methods such as IMPACT 2002+, ReCiPe Midpoint 2016, and EN 15,804+A2 also find application (Azimi and van der Spek 2025; Nurdiawati

Table 1 Overview of life cycle assessment and other environmental assessment publications considering the direct reduction – electric arc furnace route

General	Methodology				Modelling				DR- EAF	Other processes	Reducing agent	DRI/HBI charge in EAF	Change in sensi- tive EAF
	Year	Product	LCA	Impact assessment method(s)	End-of-life Allocation	CO ₂ / GWP 100	Other impact categories	Nor- mal- ized results					
Vogl et al.	2018	1 t LS	-	-	-	x	-	-	x	x	H ₂	0–100%	partial
Rechberger et al.	2020	1 t DRI	-	-	-	x	-	-	x	-	NG; H ₂	-	-
Li et al.	2021	1 t CS	x	CML 2001	-	x	x	-	x	x	CGG	10–70%*	x
Mapelli et al.	2022	1 t CS	-	-	-	x	x	-	x	x	NG; H ₂	n.s.	-
Nduagu et al.	2022	1 t DRI	x	IPCC 2013	-	x	-	-	x	x	NG;	-	-
Suer, Traverso et al.	2022	1 t CS	x	CML 2001	Cut-off	x	-	-	x	x	NG; H ₂	100%	-
Suer, Ahrenhold et al.	2022	1 t HRC	x	CML 2001	Cut-off	x	-	-	x	x	NG; H ₂	ca. 85%	-
Graupner et al.	2023	1 t CS	x	IPCC 2013	Cut-off	x	-	-	x	-	NG; H ₂	85%	-
Nurdiawati et al.	2023	1 t CS	x	EN 15,804+A2	Cut-off	x	x**	-	x	-	Bio-SG	100%	-
Ramezani Moziraji et al.	2023	1 t HRC	x	IMPACT 2002+	-	x	x	-	x	x	NG	90%	-
Zang et al.	2023	1 t CS	x	GREET 2020	-	x	-	-	x	x	NG; H ₂	75%, 100%	n.s.
Huang et al.	2024	1 t CS	x	CML 2001; ReCiPe Endpoint 2016	Cut-off	x	x	-	x	-	Bio-SG	30%	-
Ramezani Moziraji et al.	2024	1 t DRI	x	IMPACT 2002+	-	x	x	-	x	-	NG; Coal	-	-
Taji Eshkafaki et al.	2024	30 kg LS/s	x	CML 2001; ReCiPe Endpoint 2016; EPS 2015	-	x	x	-	x	-	H ₂	90%	-
Xue et al.	2024	1 t CS	-	-	-	x	-	-	x	x	COG	50–90%	x
Azimi and van der Spek	2025	1 t HRC	x	IPCC 2021; ReCiPe Midpoint 2016	Cut-off	x	x**	-	x	-	NG; H ₂	ca. 90%	-

Acronyms: Life Cycle Assessment (LCA); Global Warming Potential with a time horizon of 100 years (GWP100); Blast furnace – Basic Oxygen Furnace (BF-BOF); Electric Arc Furnace (EAF); Direct Reduction Plant (DRP); Direct Reduction – Electric Arc Furnace (DR-EAF); Liquid Steel (LS); Direct Reduced Iron (DRI); Crude Steel (CS); Hot Rolled Coil (HRC); Natural Gas (NG); Coal Gasification Gas (CGG); Bio Syngas (Bio-SG); Coke Oven Gas (COG).

* Values refer to total OBM content in the EAF and consist of hot metal and DRI

** Internal normalization

et al. 2023; Ramezani Moziraji et al. 2023, 2024). At a minimum each of the investigated papers considers CO₂ emissions or GWP100, with only eight out of 16 publications considering multiple impact categories (Azimi and van der Spek 2025; Huang et al. 2024; Li et al. 2021; Mapelli et al. 2022; Nurdiawati et al. 2023; Ramezani Moziraji et al. 2023, 2024; Taji Eshkaftaki et al. 2024). Only four of the LCA studies have calculated normalized LCIA results using standardized external normalization factors (Huang et al. 2024; Li et al. 2021; Ramezani Moziraji et al. 2023, 2024). Li et al. conduct normalization at midpoint level, and identify GWP100, Acidification Potential (AP), and Photochemical Ozone Creation Potential (POCP) as significant impact categories (Li et al. 2021). Similarly, Ramezani Moziraji et al. present normalized midpoint indicators in two separate publications. They determine GWP100, non-renewable energy, and respiratory inorganics as relevant (Ramezani Moziraji et al. 2023, 2024). However, both authors use different characterization models and normalization sets (Li et al. 2021; Ramezani Moziraji et al. 2023, 2024). Finally, Huang et al. normalize their LCA results at endpoint level, and establish the highest impact on human health (Huang et al. 2024). Only Li et al. used the normalized LCIA results to compare the DR-EAF route to the BF-BOF route across multiple impact categories (Li et al. 2021). Additionally, only the two publications by Ramezani Moziraji et al. explore process configurations similar to those initially expected in European plants (Ramezani Moziraji et al. 2023, 2024). Other researchers focus on DRP systems relying on reduction gases unlikely to be adopted in Germany, such as coal gasification gas (Li et al. 2021), or investigate future setups involving advanced configurations integrating renewable energy and carbon capture technologies (Azimi and van der Spek 2025; Huang et al. 2024; Nurdiawati et al. 2023; Taji Eshkaftaki et al. 2024).

Ten studies consider a DRP operated with natural gas, and nine consider hydrogen (Azimi and van der Spek 2025; Graupner et al. 2023; Mapelli et al. 2022; Nduagu et al. 2022; Ramezani Moziraji et al. 2023, 2024; Rechberger et al. 2020; Suer, Ahrenhold, et al. 2022; Suer, Traverso, et al. 2022a; Taji Eshkaftaki et al. 2024; Vogl et al. 2018; Zang et al. 2023). Other reducing agents such as coke oven gas, bio-syngas, coal, and coal gasification gas are analyzed as well (Huang et al. 2024; Li et al. 2021; Nduagu et al. 2022; Nurdiawati et al. 2023; Ramezani Moziraji et al. 2024; Xue et al. 2024). Varying DRI or HBI charges are considered across the studies that include the EAF process within their defined system boundaries. Some authors, such as Huang et al. and Li et al. consider lower DRI charges within the EAF, less than 50% (Huang et al. 2024; Li et al. 2021). However, a vast majority consider DRI or HBI charges higher than 75% (Azimi and van der Spek 2025; Graupner et al. 2023;

Nurdiawati et al. 2023; Ramezani Moziraji et al. 2023; Suer, Ahrenhold, et al. 2022; Suer, Traverso, et al. 2022a; Taji Eshkaftaki et al. 2024; Xue et al. 2024; Zang et al. 2023). In total, four publications include multiple furnace charge scenarios, of which just two are LCA studies (Li et al. 2021; Vogl et al. 2018; Xue et al. 2024; Zang et al. 2023). The sensitivity of the EAF to different charge scenarios is managed differently amongst these publications. Zang et al. do not specify if a change in EAF operation is considered within their study (Zang et al. 2023). Vogl et al. make a partial adaptation, adjusting electricity consumption according to the charged input materials (Vogl et al. 2018). Both the studies conducted by Xue et al. and Li et al. implement flexible EAF processes, adapting electricity and resource consumptions to the furnace charge (Li et al. 2021; Xue et al. 2024). The study of Xue et al. only conducts a CO₂ analysis, leaving just the paper by Li et al. investigating these impacts across multiple impact categories (Li et al. 2021; Xue et al. 2024).

To summarize, the literature review analyzed 16 research articles. Regarding the LCA studies, methodological heterogeneity is observed, specifically regarding aspects such as end-of-life allocation, and impact assessment methods, and normalization. Given the decarbonization potential of DR-EAF steelmaking in comparison to the BF-BOF route, most publications focus on the assessment of CO₂ emissions or GWP100. Only half of the studies consider multiple impact categories, or additional environmental aspects. One third of the LCA studies identify the relevancy of different impact categories for the DR-EAF route using standardized normalization factors. Most studies investigate DR-EAF configurations operated with natural gas or hydrogen, although alternative reduction gases are also analyzed. For the publications that include an EAF in scope, most consider charge scenarios with more than 75% DRI. Out of the four publications that consider multiple charge scenarios, only one considers a variable EAF process, and investigates multiple impact categories.

Based on the literature review, four research questions have been derived. First, what are the environmental impacts of a natural gas based DR-EAF route operated in Germany, evaluated across multiple impact categories? Second, how does the EAF charge influence the material and energy consumption of the furnace, and in turn affect the results of the LCA? Third, by applying LCA normalization, which impact categories are defined as relevant for the defined product system? Finally, do any trade-offs arise between DR-EAF and conventional (BF-BOF) steelmaking?

Table 2 Electric arc furnace charges considered within the Life Cycle Assessment

EAF charge	Scenario 1	Scenario 2	Scenario 3
scrap [%]	20%	50%	100%
DRI [%]	80%	25%	0%
HM [%]	0%	25%	0%

Acronyms: Electric Arc Furnace (EAF); Direct Reduced Iron (DRI); Hot Metal (HM)

3 Methodology

To investigate the defined research questions, an LCA was conducted following the ISO norms 14,040/44 (DIN 2020a, b), as well as the methodological guidance provided by the WSA (WSA, 2017, 2021). The coming section documents the first two phases of the LCA: the definition of goal and scope, as well as the development of the LCI. The results of the LCIA and their interpretation are presented in the results and discussion section.

3.1 Definition of goal and scope

The goal of the present research is to evaluate the environmental impacts of the DR-EAF route operated with natural gas in Germany. Germany was chosen due to the country's high contribution of primary steel production within the European union (EUROFER, 2025). Furthermore, Germany is projected to have the highest DRI capacities within the European union by 2030 (Saarstahl 2024; Salzgitter AG n.d., 2023; thyssenkrupp Steel Europe AG, 2025). The presented research is intended for the identification of environmental hotspots and is therefore relevant for LCA practitioners or sustainability experts focusing on steel production. This paper is meant for research purposes only, and is not meant to promote specific production pathways. Three scenarios

for the EAF charge have been established to aid in investigating the defined goal. These are presented in Table 2.

In the first scenario, the EAF charge reflects an expected DR-EAF configuration, featuring an elevated proportion of DRI. The scrap levels in this scenario are similar to those of BF-BOF-based steel production (Theuringer et al. 2025), as well as levels considered in other studies (Azimi and van der Spek 2025; Graupner et al. 2023; Nurdawati et al. 2023; Ramezani Moziraji et al. 2023; Suer, Traverso, et al. 2022a; Taji Eshkaftaki et al. 2024; Xue et al. 2024; Zang et al. 2023). The second scenario depicts an interim stage, representing a site where both blast furnace(s) and a DRP are in operation. Here, the EAF is charged with scrap, DRI as well as hot metal, with specific ratios being based on (Voestalpine Stahl GmbH, 2024b). Finally, the third scenario portrays a conventional scrap based EAF, instead of a DR-EAF configuration. Scenario 3 is used for interpretive purposes within the LCIA. It serves as the baseline for the EAF process, and supports the calculation of environmental impacts resulting from changes in EAF charge, including variations in material and energy consumption. For sake of transparency, the inventory data, and impact assessment for this instance is reported as well.

This study assumes cradle-to-gate system boundaries which are presented in Fig. 1. Secondary metallurgy, as well as the production and consumption of refractory materials and carbon electrodes have been excluded from the analysis due to data constraints. The system boundaries remain the same across all the defined scenarios.

A functional unit of 1 tonne of crude steel is defined and forms the basis for data collection. The LCI is based primarily on publicly available permitting documents and literature (IEAGHG, 2013; Voestalpine Stahl GmbH, 2024a; Voestalpine Texas 2013). Upstream processes, such as the

System boundaries

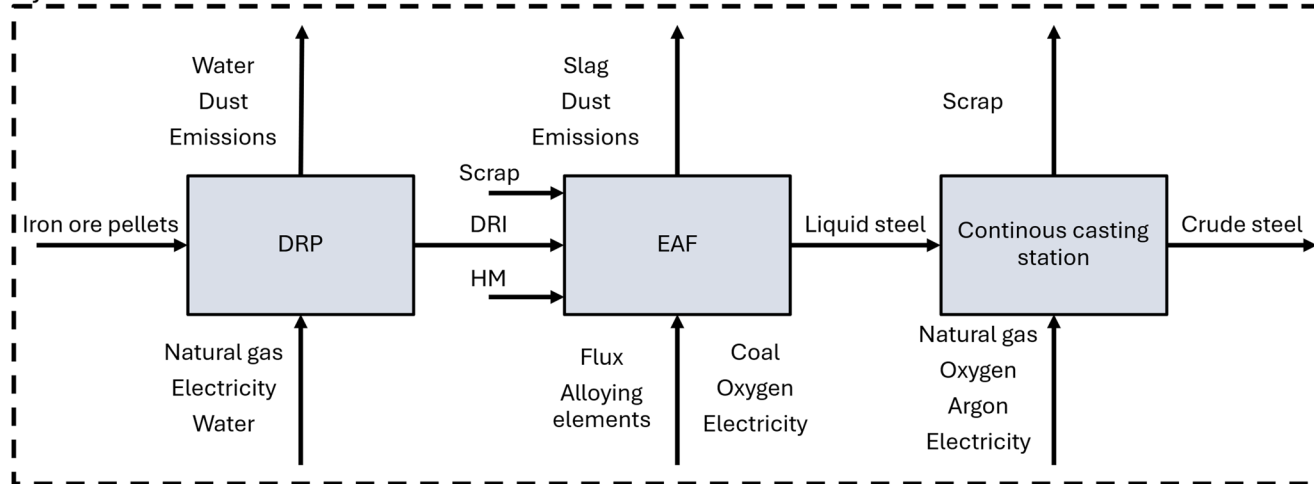


Fig. 1 System boundaries of the defined life cycle assessment. Acronyms: Direct Reduction Plant (DRP); Direct reduced Iron (DRI); Hot Metal (HM); Electric Arc Furnace (EAF)

production of iron ore pellets, are approximated using the Sphera professional database (2025.1) following the datasets listed in appendix 5 of the WSA LCI report (WSA, 2021). Additionally, in scenario 2, hot metal production has been modelled with a dataset from the Sphera database (Sphera, 2025b). Electricity is modelled according to the WSA LCI report, using the most recent version of the German grid mix, from 2022 (WSA, 2021). Additionally the German renewable electricity mix is modelled for interpretation purposes. Energy sources for both mixes are presented in Table 3. In all cases where transport is not considered within a dataset, it has been modelled separately.

The LCIA is calculated using the CML 2001 v. 2016 in addition to the normalization factors for the EU 25+3 (2000). The following impact categories are considered: Abiotic Depletion Potential for elements (ADP-e), Abiotic Depletion Potential for Fossil fuels (ADP-f), AP, Eutrophication Potential (EP), GWP100, Ozone Depletion Potential (ODP), and POCP. Toxicity related indicators are excluded from the assessment due to their limited robustness for the quantification of toxicity impacts (EC, 2018; Mikosch et al. 2022).

The assessment has been conducted using the software LCA for Experts (10.9.1.10). System expansion is used for the allocation of slag co-products. Recovery rates, and use of replacement materials are directly adopted from the WSA LCI report (WSA, 2021). For end-of-life allocation the cut-off method is applied. Following the end-of-waste definitions for iron and steel scrap defined by the European commission, all mechanical treatment of scrap material is considered as a waste treatment, which results in steel scrap entering the product system burden free (Council Regulation (EU) No 333/2011 of 31 March 2011 Establishing Criteria Determining When Certain Types of Scrap Metal Cease to Be Waste under Directive 2008/98/EC of the European Parliament and of the Council, 2011). The application of cut-off allocation deviates from the recommendations of the WSA, but is more in line with current LCA practice in the steel industry (Suer, Traverso, et al. 2022b).

A comparison to the BF-BOF route has been made. This analysis is restricted to scenario 1, based on comparable scrap shares in the metallic input. The BF-BOF route has not been modelled separately, but is instead approximated using a dataset from the Sphera database (Sphera, 2025a). The dataset documentation has been analyzed regarding methodological aspects such as system boundaries, allocation, and background datasets (Sphera, 2025a). It was determined

to be methodologically consistent with the developed LCA. Therefore, a robust comparison is ensured.

3.2 Life cycle inventory

An LCI was developed based on literature for the processes of the DRP, the EAF, and for continuous casting. The inventory of the DRP is presented in Table 4. The LCI is based on permitting records for the MIDREX plant installed in Corpus Christi, Texas by Voestalpine Texas LLC in 2016. Input flows are based on plant specific consumption rates and losses. Emissions are calculated based on stoichiometry and standardized emission factors (U.S. EPA 2024a). Therefore, a German plant should result in comparable emissions. Inputs and outputs have been converted to SI units. Whenever possible, individual values have been cross referenced with literature (Graupner et al. 2023; Lockwood Greene, 2000a, 2000b; Nurdiawati et al. 2023; Ramezani Moziraji et al. 2023, 2024; Rechberger et al. 2020; Suer, Traverso, et al. 2022a; Zang et al. 2023). Additionally, other tools provided by the United States government such as Facility Level Information on GreenHouse gases Tool (FLIGHT) and trade statistics have been used for validation as well (U.S. Census Bureau 2024; U.S. EPA 2024b).

The LCI of the EAF process was quantified by means of a flexible input/output model. To calculate the material flows associated with producing one metric tonne of liquid steel, an equation system was developed based on literature (Harvey 2020; Khattab et al. 2017; Kirschen 2021; Kirschen et al. 2011, 2017, 2021; Köhle et al. 2003; Labiscsak et al. 2011; Madias 2014; Razza and Patrizio 2010; Saeb et al. 2023). The model considers steel scrap, DRI, and hot metal as possible input materials and simplifies liquid steel as 100% metallic iron. The total mass of the EAF burden, required amounts of flux, oxygen, carbon, produced slag, and CO₂ emissions are calculated by the model. Consequently, these parameters serve as the input for the calculation of the specific electricity demand of the furnace following Köhle (Köhle et al. 2003). Finally, a static alloy mix and non-CO₂ emissions to air are based on literature (Voestalpine Stahl GmbH, 2024a). These remain the same across all three scenarios. Different furnace charge scenarios can be defined by the user, and are calculated using a weighted average of the three input materials (scrap, DRI, and hot metal). For validation purposes, calculated quantities were cross referenced with available literature (Hassan et al. 2021; Kirschen et al. 2011; Razza and Patrizio 2010;

Table 3 Energy sources for the German grid mix and renewable electricity mix for the year 2022, based on (Sphera, 2026a, 2026b)

Energy sources	Wind	Lignite	Natural gas	Hard coal	Photo-voltaic	Nuclear	Bio-gas	Hydro	Waste-to-energy	Other
DE: Grid mix	22%	20%	15%	11%	10%	6%	6%	4%	2%	4%
DE: renewable mix	59%	-	-	-	28%	-	6%	4%	1%	2%

Table 4 Life cycle inventory of a MIDREX direct reduction plant

Direct reduction plant	Unit	Value
Inputs:		
Raw materials:		
Iron ore pellets	t/t DRI	1.5
Water		
water (process and cooling)	m ³ /t DRI	7.7
Energy:		
Natural gas (feed)	GJ/t DRI	10
Electricity	kWh/t DRI	120
Outputs:		
Product:		
DRI	t/t DRI	1.0
Emissions:		
CO ₂	t/t DRI	0.55
NO ₂	t/t DRI	1.9E-04
SO ₂	t/t DRI	1.0E-05
CO	t/t DRI	3.1E-04
CH ₄	t/t DRI	4.8E-05
VOC	t/t DRI	1.7E-05
Benzene	t/t DRI	1.0E-09
Dichlorobenzene	t/t DRI	5.8E-10
Formaldehyde	t/t DRI	3.6E-08
n-hexane	t/t DRI	8.6E-07
Naphthalene	t/t DRI	2.9E-10
Toluene	t/t DRI	1.6E-09
PAH	t/t DRI	4.0E-11
Water vapor	m ³ /t DRI	1.4
Water to bay	m ³ /t DRI	6.2
PM > 10	t/t DRI	3.0E-05
PM10	t/t DRI	2.4E-05
PM2.5	t/t DRI	2.1E-05
Hg	t/t DRI	1.3E-10
Cd	t/t DRI	5.3E-10
Cr	t/t DRI	1.1E-09
Mg (as MgO)	t/t DRI	5.7E-08
Mn	t/t DRI	5.2E-09
Pb	t/t DRI	2.8E-09
Ni	t/t DRI	3.8E-09
Cu	t/t DRI	1.4E-09
Zn	t/t DRI	1.6E-08
As	t/t DRI	9.6E-11
Ba	t/t DRI	2.1E-09
Be	t/t DRI	5.8E-12
Co	t/t DRI	4.0E-11
Mo	t/t DRI	5.3E-10
Se	t/t DRI	1.2E-11
V	t/t DRI	1.1E-09

Acronyms: Hot Briquetted Iron (HBI); Direct Reduced Iron (DRI); Particulate Matter (PM); Volatile Organic Compounds (VOC); Polycyclic Aromatic Hydrocarbons (PAH)

Yang et al. 2023), and checked by industry experts. Both confirmed their validity in representing the analyzed system. The LCI of the EAF process is presented in Table 5 for the three previously defined furnace charges. The EAF

Table 5 Life cycle inventory of an electric arc furnace considering three different charge scenarios

Electric arc furnace	Unit	Value		
		Scenario 1 (20% scrap; 80% DRI)	Scenario 2 (50% scrap; 25% DRI; 25% HM)	Scenario 3 (100% scrap)
Inputs:				
Raw materials:				
Steel scrap	t/t LS	0.21	0.53	1.10
DRI	t/t LS	0.95	0.30	-
HM	t/t LS	-	0.29	-
Lime	t/t LS	0.024	0.023	0.011
Dolomite	t/t LS	0.026	0.029	0.017
Alloying elements	t/t LS	0.015	0.015	0.015
Energy:				
Coal	t/t LS	8.4E-03	0.010	0.016
Oxygen	nm ³ /t LS	26	44	29
Electricity	kWh/t LS	570	310	400
Outputs:				
Product:				
Liquid steel	t/t LS	1.00	1.00	1.00
EAF slag	t/t LS	0.20	0.16	0.081
Waste:				
EAF dust	t/t LS	0.020	0.020	0.020
Emissions:				
CO ₂	t/t LS	0.080	0.098	0.062
NO ₂	t/t LS	7.8E-04	7.8E-04	7.8E-04
CO	t/t LS	1.2E-03	1.2E-03	1.2E-03
SO ₂	t/t LS	1.3E-04	1.3E-04	1.3E-04
PCDD	t/t LS	7.8E-07	7.8E-07	7.8E-07
Ni	t/t LS	3.1E-06	3.1E-06	3.1E-06
Pb	t/t LS	3.1E-06	3.1E-06	3.1E-06
Cr	t/t LS	6.3E-06	6.3E-06	6.3E-06
Va	t/t LS	6.3E-06	6.3E-06	6.3E-06
Cd	t/t LS	3.1E-06	3.1E-06	3.1E-06
Hg	t/t LS	3.1E-07	3.1E-07	3.1E-07

Acronyms: Direct Reduced Iron (DRI); Hot Metal (HM); Electric Arc Furnace (EAF); Liquid Steel (LS); Polychlorinated dibenzodioxins (PCDD)

model, including all assumptions and literature sources are also documented in the supplementary material.

Finally, the LCI for the continuous casting process has been based on a previously conducted study by the IEA (IEAGHG, 2013). The source material considers coke oven gas for heating purposes. Within this LCA, natural gas is assumed instead. The respective quantities have been transformed based on the lower heating values of both gasses. The LCI is presented in Table 6.

Table 6 Life cycle inventory of a continuous casting station

Continuous casting	Unit	Value
Inputs:		
<i>Raw materials:</i>		
Liquid steel	t/t CS	1.03
<i>Energy:</i>		
Natural gas	GJ/t CS	0.019
Oxygen	nm ³ /t CS	2.0
Argon	nm ³ /t CS	0.11
Electricity	kWh/t CS	10
Outputs:		
<i>Product:</i>		
Steel slab	t/t CS	1.00
<i>Waste:</i>		
Steel scrap	t/t CS	0.035
<i>Emissions:</i>		
n.a.		

Acronyms: Crude Steel (CS)

4 Results and discussion

This section documents the results of the LCIA and their interpretation. As previously mentioned, four research questions have been derived from the literature review. The first two are:

1. What are the environmental impacts of a natural gas based DR-EAF route in Germany for multiple impact categories?
2. How do different OBM affect the EAF process, and consequently the results of the LCA?

To answer these research questions, the LCIA results are presented, and environmental hotspots are identified across the seven defined impact categories. The influence of both OBM on the LCA results is distinguished in this section, followed by a more in depth analysis of process contributions to GWP100.

The results of the LCIA are presented in two distinct forms. The first, as is shown in Table 7, presents the environmental impacts grouped according to the main industrial processes of DRI production, hot metal production, the EAF process and continuous casting. This representation includes all upstream impacts associated with these processes. For example, the production of iron ore pellets is included in DRI production. The environmental impacts for the EAF process have been further partitioned into two sub-categories, as is shown in Fig. 2. The first, denoted as “EAF – 100% scrap based”, acts as a baseline and represents the environmental impacts stemming from the operation of a 100% scrap charged EAF, as defined in scenario 3. The column “EAF – influence of OBM”, quantifies additional

Table 7 Life cycle impact assessment results of scenarios 1–3, grouped according to main industrial processes

Impact category	Scenario	Unit	Total	DRI production	HM production	EAF – 100% scrap based	EAF - influence of OBM	Continuous casting
ADP-E	1	kg Sb eq./t CS	8.3E-04	2.3E-04	-	6.0E-04	8.4E-06	1.5E-06
	2	kg Sb eq./t CS	6.5E-04	7.1E-05	-4.3E-08	-	-1.8E-05	-
	3	kg Sb eq./t CS	6.0E-04	-	-	-	-	-
ADP-f	1	MJ/t CS	1.8E+04	1.4E+04	-	3.3E+03	6.6E+02	7.2E+01
	2	MJ/t CS	1.3E+04	4.5E+03	5.3E+03	-	-4.6E+02	-
	3	MJ/t CS	3.4E+03	-	-	-	-	-
AP	1	kg SO ₂ eq./t CS	3.3E+00	2.1E+00	-	1.2E+00	8.4E-02	6.9E-03
	2	kg SO ₂ eq./t CS	3.0E+00	6.4E-01	1.2E+00	-	-6.3E-02	-
	3	kg SO ₂ eq./t CS	1.2E+00	-	-	-	-	-
EP	1	kg PO ₄ ³⁻ eq./t CS	4.8E-01	2.7E-01	-	1.9E-01	1.8E-02	1.5E-03
	2	kg PO ₄ ³⁻ eq./t CS	3.9E-01	8.3E-02	1.3E-01	-	-1.3E-02	-
	3	kg PO ₄ ³⁻ eq./t CS	1.9E-01	-	-	-	-	-
GWP100	1	kg CO ₂ eq./t CS	1.5E+03	9.8E+02	-	3.7E+02	1.1E+02	5.4E+00
	2	kg CO ₂ eq./t CS	1.3E+03	3.1E+02	6.0E+02	-	2.1E+01	-
	3	kg CO ₂ eq./t CS	3.7E+02	-	-	-	-	-
ODP	1	kg R11 eq./t CS	2.2E-08	1.3E-08	-	6.5E-09	2.6E-09	1.7E-10
	2	kg R11 eq./t CS	1.2E-08	4.0E-09	3.0E-09	-	-1.3E-09	-
	3	kg R11 eq./t CS	6.7E-09	-	-	-	-	-
POCP	1	kg C ₂ H ₄ eq./t CS	2.9E-01	1.7E-01	-	1.1E-01	6.2E-03	6.0E-04
	2	kg C ₂ H ₄ eq./t CS	3.5E-01	5.4E-02	2.0E-01	-	-5.4E-03	-
	3	kg C ₂ H ₄ eq./t CS	1.1E-01	-	-	-	-	-

Acronyms: Abiotic Depletion Potential for Elements (ADP-e); Abiotic Depletion Potential for Fossil Fuels (ADP-f); Acidification Potential (AP); Eutrophication Potential (EP); Global Warming Potential with a time horizon of 100 years (GWP100); Ozone Depletion Potential (ODP); Photochemical Ozone Creation Potential (POCP); Crude Steel (CS); Trichlorofluoromethane (R11)

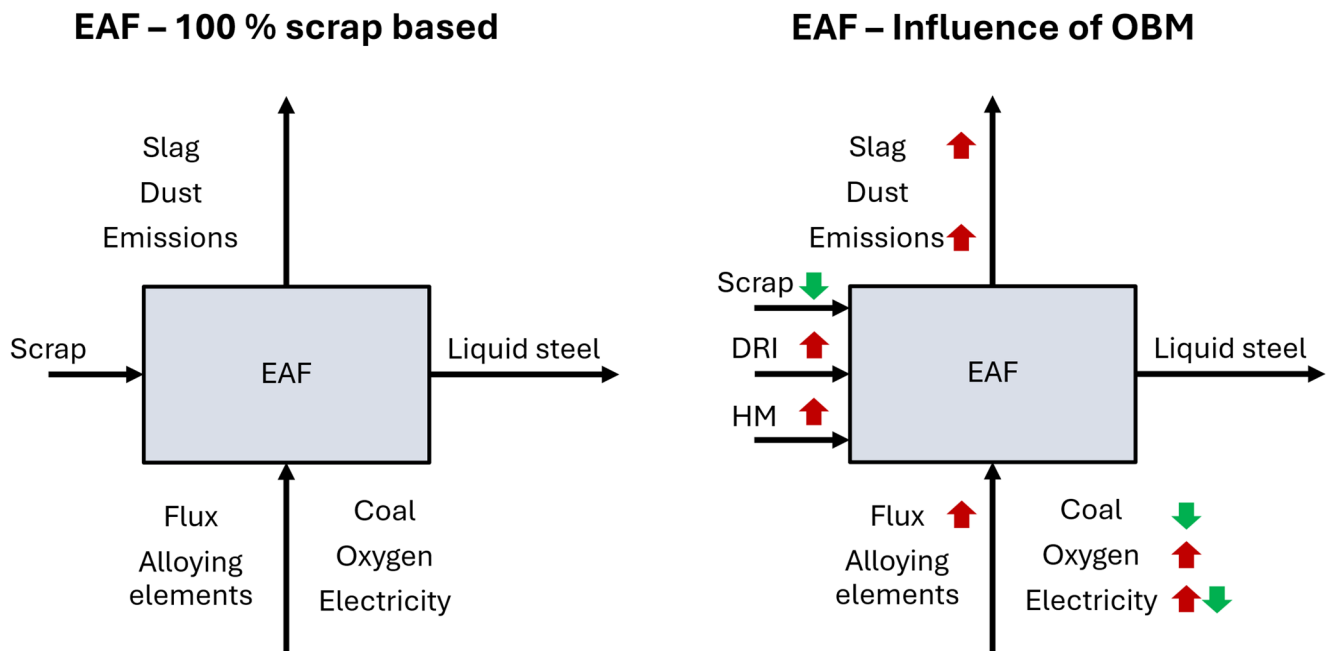


Fig. 2 Sub-partitioning of the electric arc furnace process. Acronyms: Direct Reduction Plant (DRP); Direct reduced Iron (DRI); Hot Metal (HM); Electric Arc Furnace (EAF)

impacts from variations in material and energy consumption brought on by the substitution of scrap by DRI or hot metal. The total impact attributed to the EAF is equal to the sum of both subcategories. The second manner in which LCIA results are introduced are as individual process contributions for each of the three defined scenarios. These values are presented in the supplementary material. For visualization purposes, processes contributing less than 5% to any given impact category have been grouped in “other”.

The environmental hotspots are presented as grouped results and individual process contributions in Figs. 3 and 4 respectively. The results of scenario 1 are presented in quadrant (a) of both figures. With the exception of ADP-e, the production of DRI has the highest contributions to the assessed impact categories. The overall contribution of DRI production varies between 27% (ADP-e) and 78% (ADP-f) of total impact. The share of impacts stemming from the EAF make up 73% of contributions to ADP-e, as well as resulting in between 22% (ADP-f) and 44% (EP) of total impact in other impact categories. A DRI charge of 80% increases the environmental impact of the EAF process across all impact categories, when compared to a 100% scrap based EAF. In particular, GWP100 and ODP are affected. For these impact categories operational changes of the EAF account for 8% and 12% of overall LCIA results respectively.

As is shown in Fig. 4 (a), relevant process contributions are denoted for the production of alloying elements, iron ore pellets, natural gas, as well as the generation of electricity and the direct emissions of the DRP and EAF. The energy intensive production process of ferroalloys causes the alloy

mix to contribute between 4% and 10% of impacts to ADP-f, AP, EP, GWP100 and POCP (Eric 2024). However, the main contribution is observed for ADP-e, where it makes up 66% of the total impact, due to the depletion of metal elements including iron, chromium and manganese. The production of iron ore pellets is observed as another hotspot across multiple impact categories. The reason for this is stipulated to be the induration process during pellet production. This process requires high amounts of thermal energy, which is generated through the consumption of heavy fuel oil (Sphera, 2026c). Resultingly pellet production leads to an ADP-f of $2.6E+03$ MJ/t CS, and GWP100 of 0.24 t CO₂ eq./t CS which accounts for 14% and 16% of total impact, respectively. The dataset used for modelling assumes a mix of pellets which are produced in Australia, Brazil and Canada (Sphera, 2026c). Closer inspection of the database documentation reveals that the combustion of heavy fuel oil in Brazil is tied to 1.7 kg SO₂/GJ fuel input and 0.20 kg NO_x/GJ fuel input (Sphera, 2026d). This would also explain the high contributions to AP (53%) and POCP (38%). As a fossil fuel, the production of natural gas mainly affects ADP-f, accounting for 11 GJ/t CS. Additionally, lesser contributions are denoted across other impact categories. The consumption of natural gas in the DRP results in a high contribution to GWP100, at 0.54 t CO₂ eq./t CS, which accounts for 37% of overall emissions to this impact category. Electricity generation has a relevant contribution to all assessed impact categories ranging from 10% (ADP-e) to 47% (ODP). As the grid mix comprises a number of power generating technologies, these impacts have different causes. Electricity

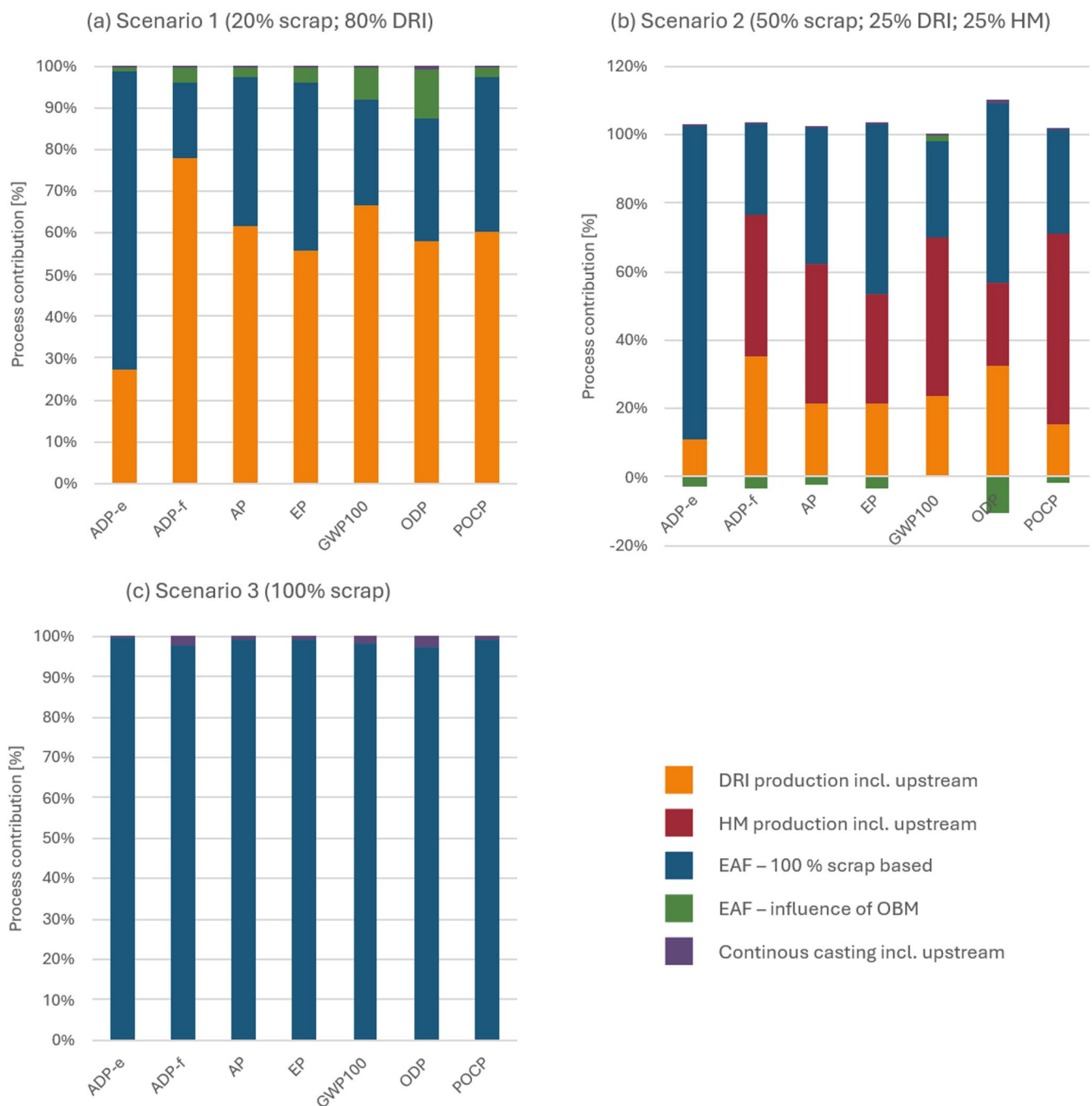


Fig. 3 Environmental hotspots of scenarios 1–3, grouped according to main industrial processes. Acronyms: Direct reduced Iron (DRI); Hot Metal (HM); Electric Arc Furnace (EAF); Ore Based Metallics (OBM)

generation from wind and photovoltaic made up 32% of the German grid mix in 2022. In both cases, environmental impacts stemming from the manufacture/installation of generating technologies are included, and would explain the impacts to ADP-e due to the consumption of rare earths or semiconductor materials (Alves Dias et al. 2020; Siva Ramkumar et al. 2022). 47% of impacts to ODP are due to the generation of electricity. These impacts stem almost exclusively from photovoltaics. Previous research has linked the

production of photovoltaic modules to ODP related impacts, although this cannot be explicitly verified here (Fu et al. 2015). The remaining impacts to ADP-f, AP, EP, and POCP from the electricity generation stem mainly from fossil fuel and biogas fired powerplants. Finally, due to the direct emissions of CO₂, sulfur dioxide, and nitrogen dioxide, the EAF directly contributes between 6% (GWP100) and 22% (EP and POCP) of environmental impacts.

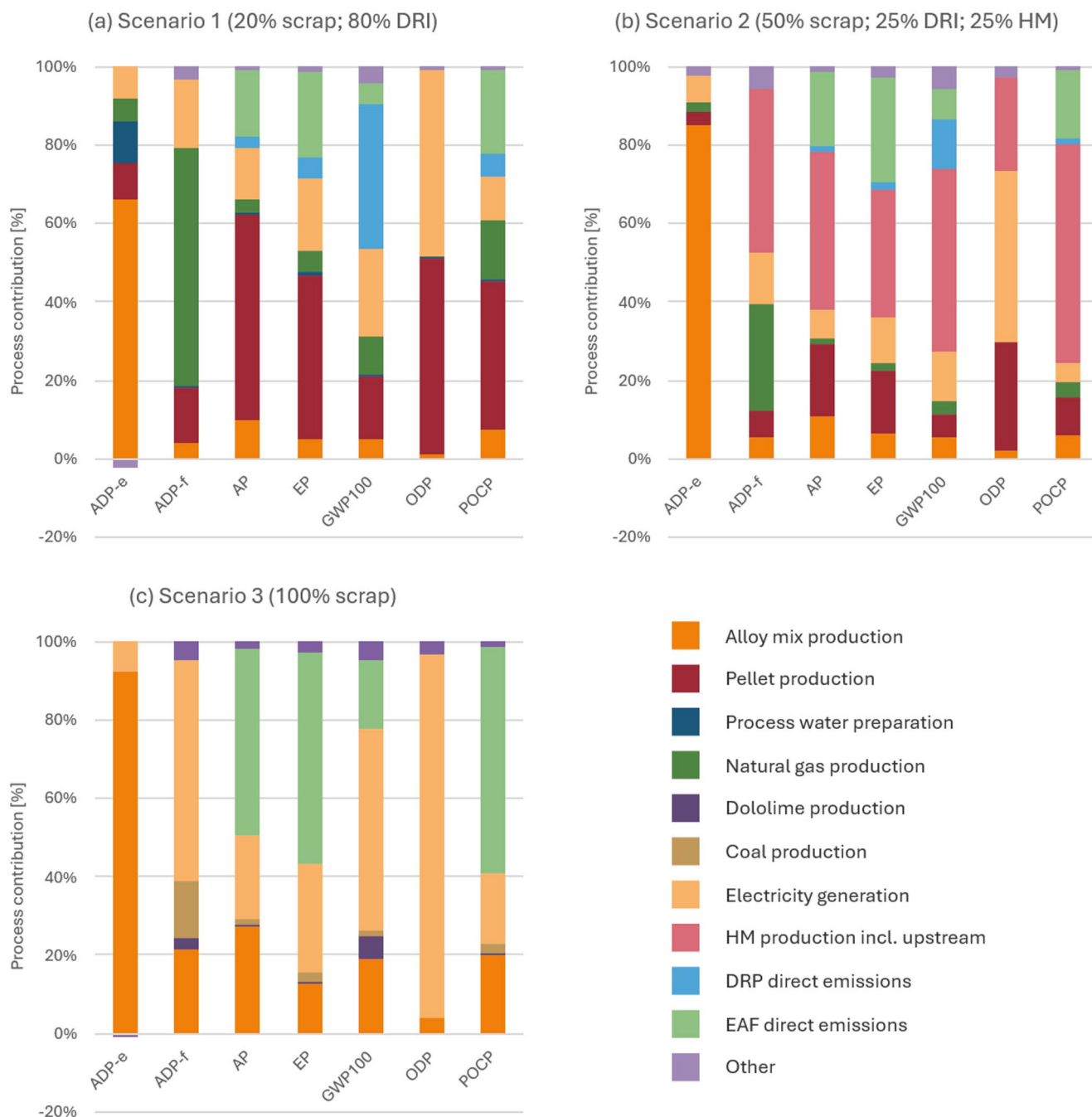


Fig. 4 Environmental hotspots of scenarios 1–3, individual process contributions. Acronyms: Hot Metal (HM); Direct Reduction Plant (DRP); Electric Arc Furnace (EAF)

To highlight the effects of the furnace charge on LCA results of scenario 1, the process contributions to “EAF – influence of OBM” are displayed in Fig. 5 for GWP100. Compared to the reference EAF with a 100% scrap charge, changes in material and energy consumption lead to an increase in GWP100 of 0.11 t CO₂ eq./t CS. The increased electricity demand of the furnace results in 0.08 t CO₂ eq./t CS, due to the higher slag quantities and the endothermic reaction of iron oxide and carbon in the slag phase

(Kirschen et al. 2011). Note, that the model used to calculate the energy consumption of the EAF considers a cold DRI charge (Köhle et al. 2003). In the defined process configuration, in which the DRP and EAF are assumed to be operated at the same site, hot charging presents a more efficient alternative, leading to reduced energy consumption in the EAF and offering both environmental and economic advantages (Razza and Patrizio 2010). The increase in slag volume brought on by charging DRI leads to additional effects.

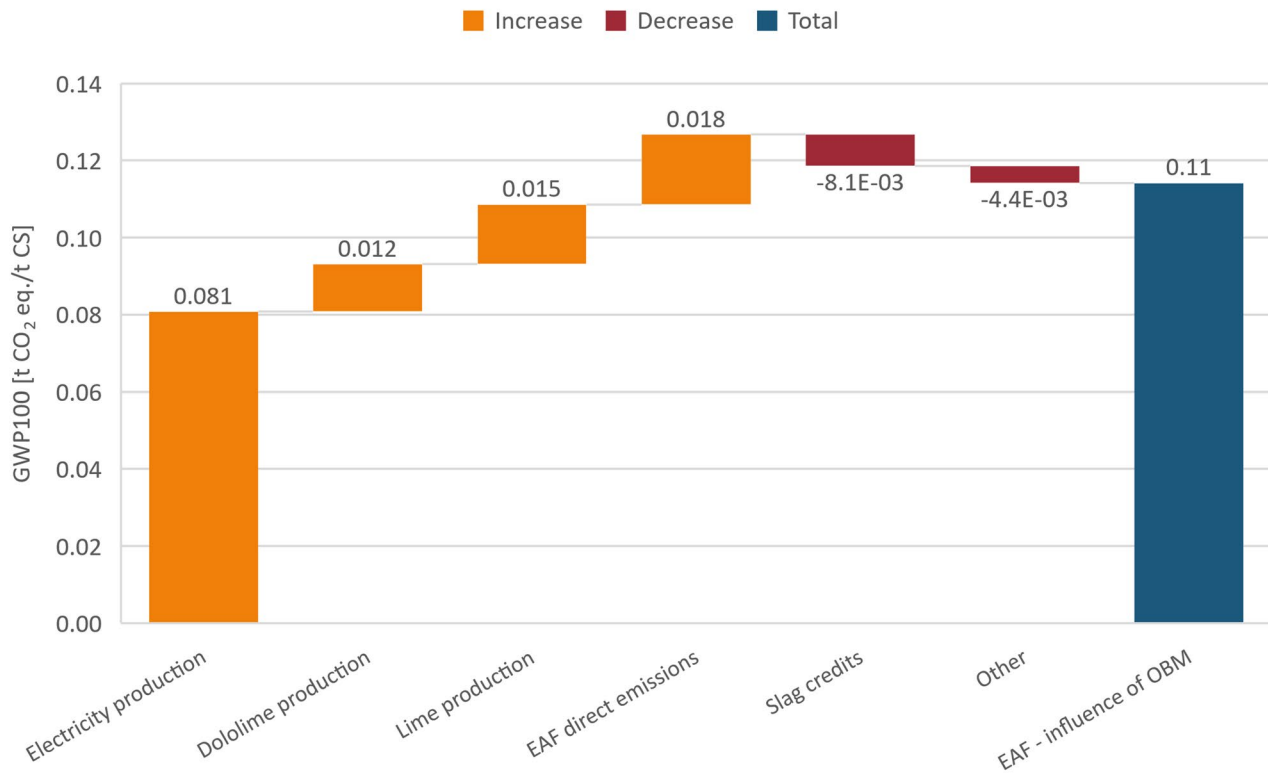


Fig. 5 Influence of ore based metallics on the results of GWP100 for scenario 1 (20% scrap; 80% direct reduced iron). Acronyms: Electric Arc Furnace (EAF); Ore Based Metallics (OBM)

More flux is required to maintain slag basicity which increases the contributions to GWP100 by 0.027 t CO₂ eq./t CS. Additionally, more carbon input is required for effective foaming. This is partially supplied by the carbon content of the DRI. Ultimately, this results in higher direct emissions of the EAF, which increase by 0.018 t CO₂ eq./t CS, compared to the 100% scrap based EAF. Finally, a greater slag credit is achieved, which in this figure is represented with a negative value of -8.1E-03 t CO₂ eq./t CS.

Figure 6 documents individual process contributions to GWP100 for Scenario 1. A total impact of 1.5 t CO₂ eq./t CS is observed. More than 58% of these impacts stem from upstream processes. In particular, the generation of electrical energy, the production of iron ore pellets and natural gas contribute 0.32, 0.24, and 0.14 t CO₂ eq./t CS respectively. Additionally, the defined alloy mix contributes 5% of impacts to GWP100 (0.072 t CO₂ eq./t CS), even though it makes up less than 15 kg/t CS. The highest process contribution stems from the direct emissions of the DRP, with 0.54 t CO₂ eq./t CS. This corresponds to 0.55 t CO₂ eq./t DRI, and is in line with previously published research (Graupner et al. 2023; Nduagu et al. 2022; Rechberger et al. 2020; Suer, Traverso, et al. 2022a). These impacts are

caused by the MIDREX reformer in which natural gas as well as the recirculated top gas are reformed into syngas.

Figure 3 (b) and Fig. 4 (b) show the different environmental hotspots of scenario 2 including a mixed charge of 50% scrap, 25% DRI, and 25% hot metal. Similarly to the previous scenario, the production of OBM, leads to the highest contributions to all impact categories except for ADP-e. For these impact categories, OBM production accounts for between 57% (ODP) and 77% (ADP-f) of overall impacts. The production of hot metal in the blast furnace causes higher environmental impacts to ADP-f, AP, EP, GWP100, and POCP, whereas the production of DRI contributes more to ADP-e and ODP. Responsible processes are similar to those denoted in scenario 1. However, due to the difference in furnace charge composition, individual values differ. For example, contributions from iron ore pellets are less pronounced, ranging from 4% (ADP-e) to 28% (ODP) due to less DRI being charged in this scenario. Once more hot metal production is observed as a hotspot for scenario 2. However, this process does not just represent direct emissions, but includes upstream impacts, which could not be disaggregated further (Sphera, 2025b). For ADP-e in particular, hot metal production leads to slightly negative impacts (-4.3E-08 kg Sb eq./t CS), due to the credits

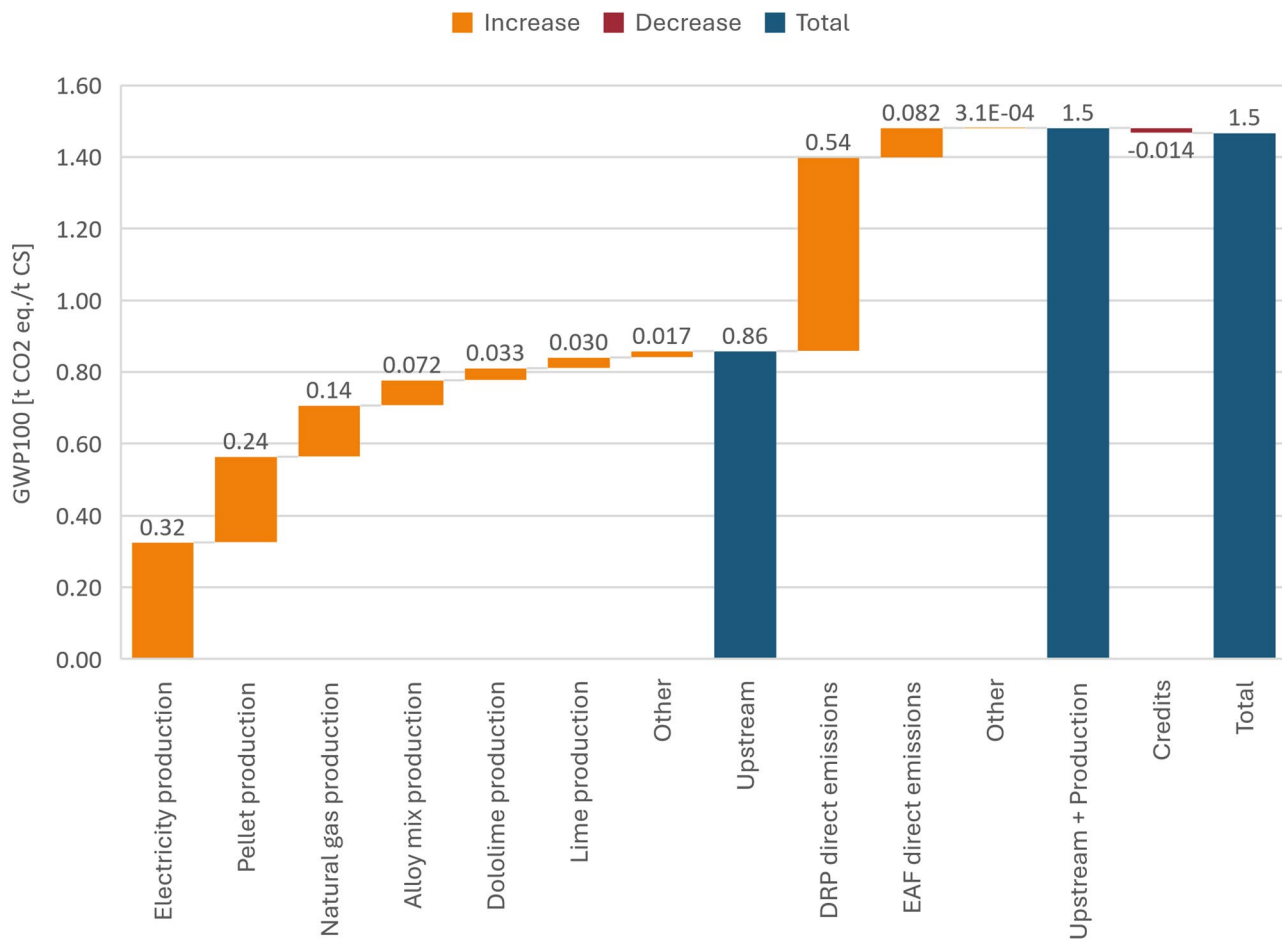


Fig. 6 Process contributions to GWP100 for scenario 1 (20% scrap; 80% direct reduced iron). Acronyms: Direct Reduction Plant (DRP); Electric Arc Furnace (EAF)

generated for co-products in the coke batteries, granulated blast furnace slag, and electricity produced from off-gasses (Sphera, 2025b). It is hypothesized that impacts to other impact categories originate from the coal/coke based metallurgy, as well as the incineration of blast furnace and coke oven gas in the powerplant. The defined OBM charge of 25% DRI and 25% hot metal has an overall positive influence on the operation of the EAF, leading to reductions in potential environmental impacts when compared to 100% scrap based operation. In general, the observed reductions are brought on by the decreased electricity consumption of the EAF, which is attributed to the increased thermal energy entering the furnace through the charged hot metal. These savings are most pronounced for the impact category ODP (ca. 10%), which is strongly influenced by impacts stemming from power generation by photovoltaics. However, any operational benefits are compensated by the upstream emissions tied to the production of the OBM themselves, underlining the need for a life cycle perspective. Additionally, as

is shown in Fig. 7, the CO₂ savings of decreased electricity demand are offset for GWP100 by an increase in flux consumption and elevated direct emissions.

The increase in flux is attributed to elevated silica input into the system. This occurs either directly via the DRI charge, where silica is present as part of the gangue, or indirectly through hot metal, where silicon is introduced in a dissolved form. Due to the oxidizing atmosphere of the EAF, silicon reacts to silica, which in turn influences the slag composition. Additional flux is required to maintain the proper slag basicity and results in an increase in GWP100 of 0.031 t CO₂ eq./t CS. As in scenario 1, foaming the increased slag volume brought on by the OBM requires additional carbon input. The carbon input ultimately reacts to CO₂ and is expelled from the furnace in the off-gas. As a result, the direct emissions of the EAF increase by 0.037 t CO₂ eq./t CS. Additionally, higher slag credits are achieved for the increase in slag volume, which is depicted in this diagram as a negative value.

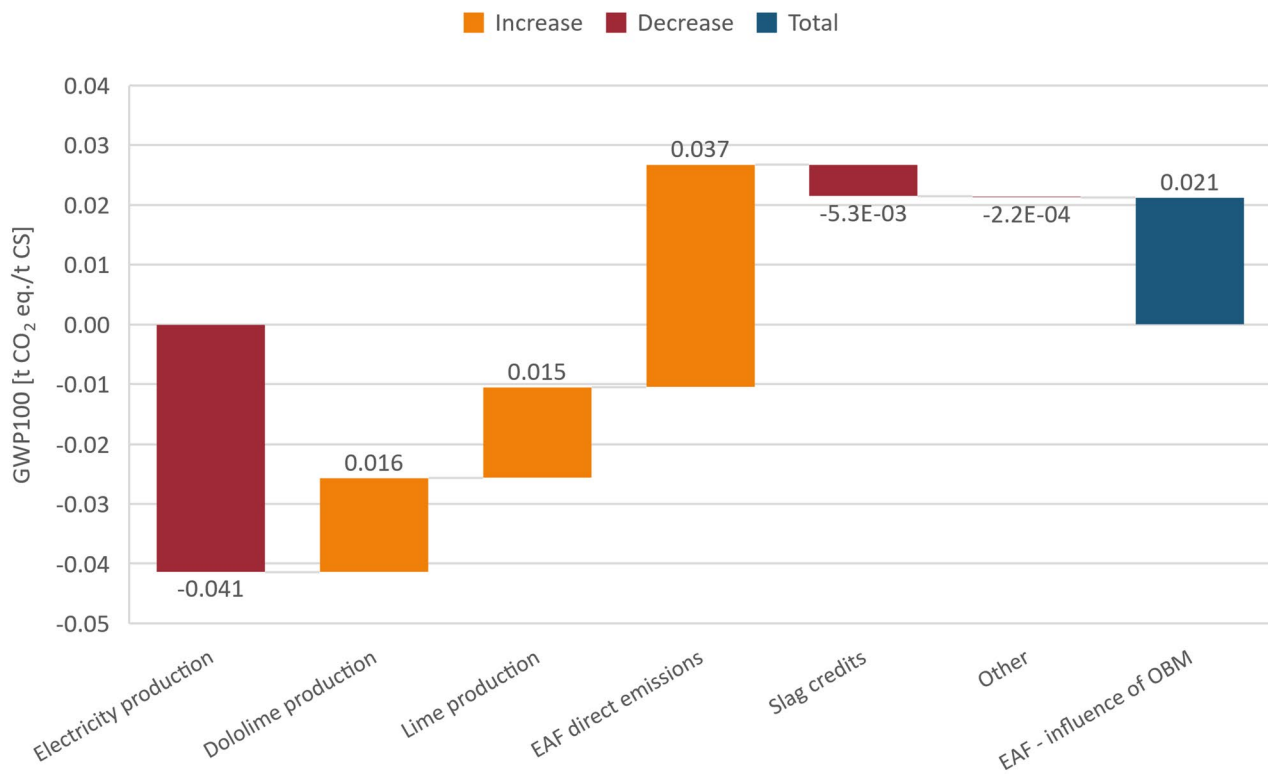


Fig. 7 Influence of ore based metallics on the results of GWP100 for scenario 2 (50% scrap; 25% direct reduced iron; 25% hot metal). Acronyms: Electric Arc Furnace (EAF); Ore Based Metallics (OBM)

Process contributions to GWP100 are presented in Fig. 8 for scenario 2. Considering an EAF charge of 50% scrap, 25% DRI and 25% hot metal, the GWP100 equals 1.3 t CO₂ eq./t CS. The highest process contributions are observed for the production of hot metal, with 0.60 t CO₂ eq./t CS, followed by the direct emissions of the DRP and production of electricity, both with 0.17 t CO₂ eq./t CS. Note that in this representation the hot metal value also includes upstream impacts. This, in addition to the higher scrap charge considered in this scenario, diminishes the remaining upstream impacts to 0.44 t CO₂ eq./t CS. Individual contributions from the production of iron ore pellets, natural gas, as well as direct emissions from the DRP are lower, due to the decreased amount of DRI in the EAF charge from 80% to 25%. The inclusion of hot metal in the EAF charge proves to be beneficial in EAF operation, reducing the electrical energy demand by around 90 kWh/t CS. However, this advantage is offset by an increase in flux material and direct emissions, as was discussed previously.

The environmental hotspots of scenario 3 are presented in Fig. 3 (c) and Fig. 4 (c). Due to the lack of OBM in this scenario, the relative contribution of the EAF is inflated to upwards of 98% for all impact categories. As a result, previously identified hotspots such as the production of iron

ore pellets or natural gas are no longer present in this scenario. As steel scrap is assessed as burden free, the overall impacts of this scenario are much lower. Therefore, the relative contribution of the remaining processes increases. Consequently, processes which were previously grouped in the “other” category, now make up a more considerable contribution. This is observed mainly for dolomite production which now accounts for 6% of impacts to GWP100, due to the calcination process. Additionally, more coal is required for the EAF process. While less carbon is required overall, more coal must be injected to compensate the negligible amounts of carbon entering the furnace through the scrap charge (Madias 2014). This mostly affects ADP-f, resulting in 15% of the overall impact, which corresponds to 0.50 GJ/t CS.

A more in depth analysis is presented for GWP100 in Fig. 9. With 0.37 t CO₂ eq./t CS, the total GWP100 of this scenario is much lower than those discussed for scenarios 1 and 2. The main reasons for this are the precluded direct emissions of the DRP and the blast furnace. Furthermore, upstream emissions are 0.31 t CO₂ eq./t CS due to steel scrap being assessed using the cut-off method. In this scenario the major environmental hotspot is the generation of electrical energy with 0.19 t CO₂ eq./t CS, which accounts

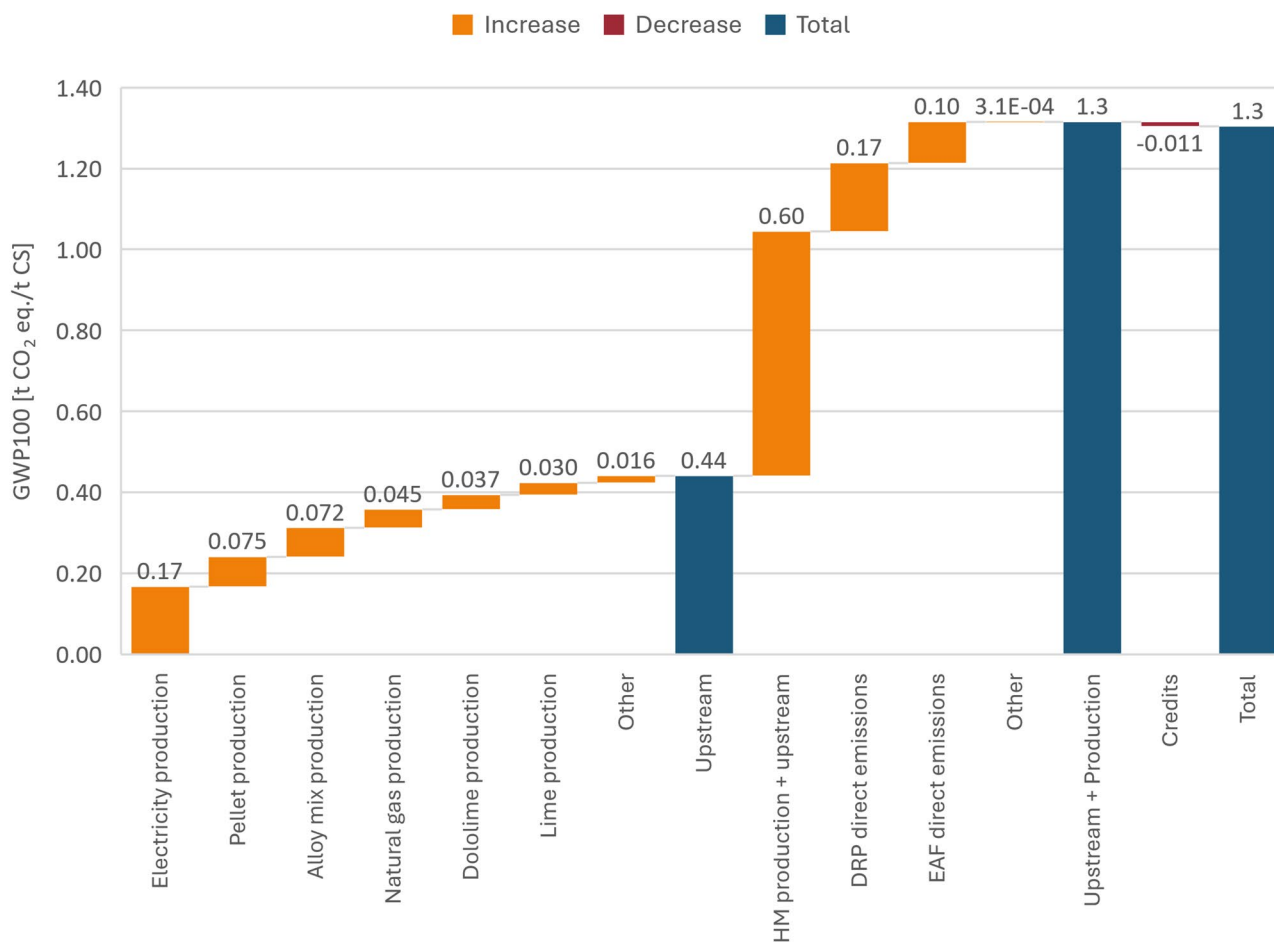


Fig. 8 Process contributions to GWP100 for scenario 2 (50% scrap; 25% direct reduced iron; 25% hot metal). Acronyms: Hot Metal (HM); Direct Reduction Plant (DRP); Electric Arc Furnace (EAF)

for more than half of the total environmental impact. Additionally, the alloy mix with 0.072 t CO₂ eq./t CS, and the direct emissions of the EAF with 0.064 t CO₂ eq./t CS are other relevant contributions.

The LCA results are significantly affected by steel scrap being assessed using the cut-off method. As a major part of the input materials is assessed without any environmental burdens, the comparability between scenarios with different scrap recycling rates is limited. Decarbonization technologies that process more scrap appear to be environmentally favorable, even though it is unlikely that an improvement in environmental performance is achieved at a global level (Arnold et al. 2025; ResponsibleSteel, 2022).

The coming section aims to answer research questions three and four. These are:

1. What is the relative significance of different impact categories for the defined product system?

2. Do any trade-offs arise between DR-EAF and BF-BOF steelmaking?

To answer research questions three and four, the normalized LCIA results are introduced. This analysis makes use of the CML normalization factors defined for the EU 25+3 (2000). Trade-offs are solely identified between scenario 1 and the BF-BOF route, as the defined scrap shares in the other scenarios limit direct comparability. The normalized LCIA results are presented in Fig. 10. ADP-f, AP, GWP100, and POCP are identified as relevant impact categories, accounting for 97% of the total normalized impacts for scenario 1, and 99% of total impacts for the BF-BOF production route. For the DR-EAF process configuration this corresponds to the findings of Li et al. with the exception of ADP-f (Li et al. 2021). This could be due to the different reduction gas considered in their research. ADP-e, EP, and ODP each contribute less than 2% to the overall region equivalents.

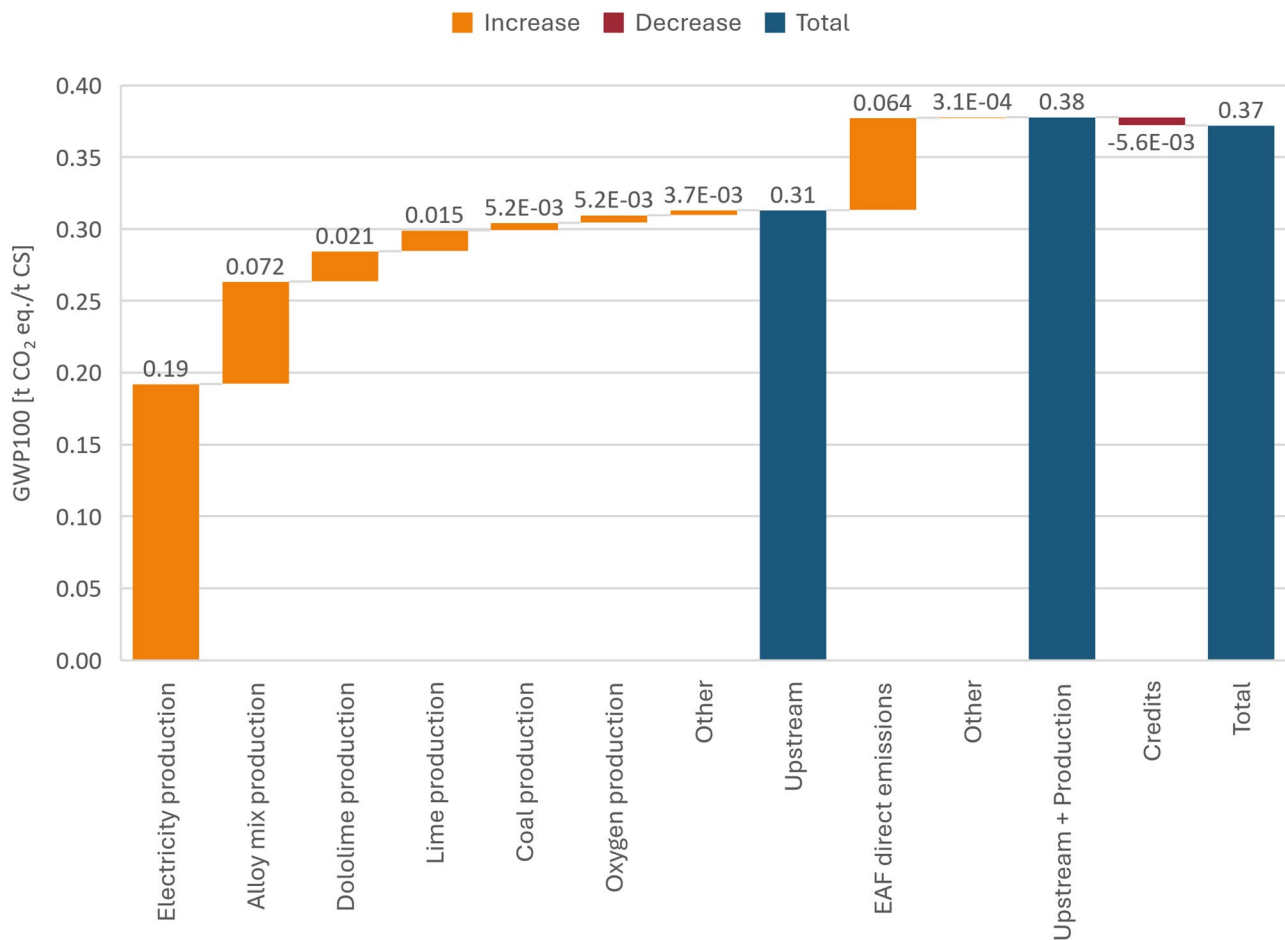


Fig. 9 Process contributions to GWP100 for scenario 3 (100% scrap). Acronyms: Electric Arc Furnace (EAF)

Reductions compared to the BF-BOF route are observed for AP (-13%), GWP100 (-26%), and POCP (-57%). However, a relevant trade-off is identified for ADP-f (+10%). Both AP and POCP are strongly influenced by sulfur dioxide and nitrogen oxide emissions, with POCP being affected by carbon monoxide as well. All of these components are released during the sintering process for BF-BOF steelmaking. Other authors have reported that the sintering is responsible for 23% of impacts to AP, and 55% to POCP for BF-BOF steelmaking (Backes et al. 2021). The absence of this process in the DR-EAF route could explain the gaps observed in the normalized results. However, as the BF-BOF route is modelled using an aggregated process, further investigation of this hypothesis is not possible. Regarding GWP100, direct emissions are greatly reduced due to the substitution of coal with natural gas as the main energy source. Additionally, the total energy consumption of the DRP is lower on account of the top gas being recirculated, before being ultimately combusted in the reformer (Suer, Ahrenhold, et al. 2022). However, a different trend is observed for ADP-f. Apart from the

consumption of different fossil fuels, this is attributed to the shift towards electric steelmaking. In general, the electricity consumption of the DR-EAF route is higher than that of the BF-BOF. For example, the electrical energy demand of scenario 1 equals 2.5 GJ/t CS. In contrast, other authors report electricity demands for the BF-BOF route varying between 0.51 and 0.97 GJ/t CS (Azimi and van der Spek 2025; Li et al. 2021; Xue et al. 2024; Zang et al. 2023). Furthermore, integrated steel sites are able to produce their own electricity through the combustion of off-gasses in a powerplant. Produced electricity exceeds onsite demand, and leads to a credit for the electricity supplied to the grid (Suer et al. 2021; Suer, Traverso, et al. 2022a; Zacharopoulos et al. 2025). In both routes, modelling (credits for) electricity using the German grid mix significantly influences the results of ADP-f. This is due to the high percentage of fossil fuels currently used in power generation (BNetzA 2025; Sphera 2026a). To highlight this effect, the LCIA was calculated again for scenario 1 using the German renewable mix, as can be seen in Fig. 10. Compared to the baseline

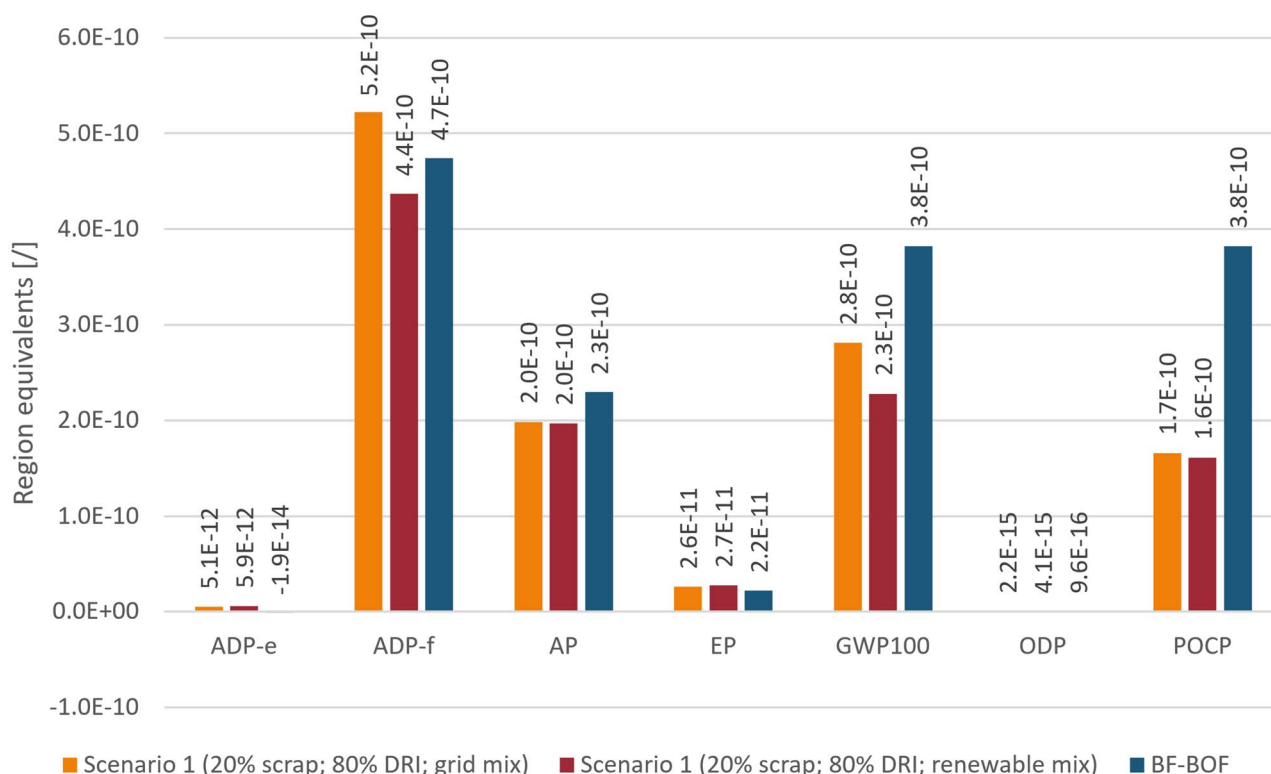


Fig. 10 Comparison of normalized LCA results for the direct reduction – electric arc furnace route with 20% scrap and 80% DRI (scenario 1) and the blast furnace – basic oxygen furnace route. Acronyms: Direct reduced Iron (DRI); Blast Furnace – Basic Oxygen Furnace (BF-BOF)

calculated with the grid mix, the results of ADP-f decrease by 16%. The previously observed trade-off in relation to the BF-BOF route is thereby compensated. With this change in place the DR-EAF route leads to improvements across all relevant impact categories and highlights the importance of decarbonizing the entire value chain.

A few limitations should be mentioned. First and foremost is the reliance on secondary data sources. In particular, the model used to quantify changes in EAF operation as a function of the furnace charge is based on multiple literature sources and assumptions. While the results of the model have been verified, modelling is tied to inherent uncertainties which should be recognized. A more robust approach would be developing the inventory based on primary data from a company. However, this was not possible as part of this research. Second, the manner in which electricity consumption of the EAF is calculated assumes a cold DRI charge. In the defined process configuration, in which the DRP and EAF are assumed to be located on the same site, hot charging of DRI is an obvious choice, and would result in savings for environmental impacts as well as costs. Third, both hot metal production and the BF-BOF configuration are approximated using aggregated datasets. This limits the investigation of certain environmental impacts, in particular regarding the credits received for co-products. Finally, the

direct comparability of the three defined scenarios is limited due to the chosen end-of-life allocation method. As steel scrap is assessed as “burden free” it significantly influences the results of the LCA, and makes decarbonization efforts based on increased scrap recycling appear environmentally favorable, despite limited global benefits.

5 Conclusions and outlook

This paper set out to investigate the environmental impacts of a modern DR-EAF route operated in Germany. A literature review was conducted to gain an overview of sustainability research on this production route, and to identify further research questions. The literature review identified methodological heterogeneity among LCA publications, concerning aspects such as end-of-life allocation, impact assessment methods and LCA normalization. Many authors focus on the investigation of CO₂ emissions or GWP100, omitting other types of environmental impacts. Based on this, four research questions were developed and investigated. The results identify the production of OBM (DRI and hot metal) as environmental hotspots across all investigated impact categories, except ADP-e. High contributing processes are identified in the production of the alloy mix,

pellets, natural gas, the generation of electricity in addition to direct emissions of the DRP and EAF. Integrating OBM into the EAF charge has a considerable effect on the environmental impacts of the EAF process, in particular for GWP100 and ODP. In scenario 1, a DRI charge of 80% leads to an increase in environmental impact of up to 12%. Similarly, when the OBM charge is modified to 25% DRI and 25% hot metal, this leads to operational savings of up to 10%, due to the lower electric energy demand resulting from charging hot metal. However, this benefit is offset by the production of the OBM themselves. The normalized LCIA results identify ADP-f, AP, GWP100, and POCP as relevant impact categories for both DR-EAF as well as BF-BOF steelmaking. The DR-EAF process configuration leads to an improvement in environmental performance for all assessed impact categories except for ADP-f in which the impact increases by 10%. This trade-off has been linked to the transition to electric steelmaking, due to the high ADP-f factor of the German grid mix. It is shown that through the use of renewable energies, this effect can be compensated, leading to an improvement in environmental performance compared to the BF-BOF route across all relevant impact categories. Future research should focus on a more in depth comparison of the DR-EAF and BF-BOF routes, concentrating on the influence system expansion credits on the overall LCA results. Additionally, the comparison to other process configurations such as the direct reduction – submerged arc furnace – basic oxygen furnace route could provide valuable insights. The comparability concerns originating from the burden free assessment of steel scrap should be addressed. Finally, expanding the purely environmental assessment to cover both social and economic factors would better facilitate a triple bottom line approach to the sustainability assessment of this emerging steel production route.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11367-026-02645-w>.

Author contributions Gijs Krekel: Conceptualization, Data Curation, Methodology, Investigation, Software, Visualization, Validation, Formal analysis, Writing – Original Draft, Writing – Review & Editing. Julian Suer: Writing – Review & Editing, Supervision. Nils Jäger: Writing – Review & Editing, Supervision. Marzia Traverso: Writing – Review & Editing, Supervision, Project Administration.

Funding Open Access funding enabled and organized by Projekt DEAL. This research was conducted as a part of the tkH2steel project and was funded by the Federal Ministry for Economic Affairs, Industry, Climate Action and Energy of the State of North Rhine-Westphalia (MWIKE NRW) under the funding code 03H2I047.

Data availability The authors declare that the data used to support this research is reported within the paper and its supplementary material.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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