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Low-carbon primary steelmaking using direct reduction and electric arc furnaces: Prospective environmental impact assessment

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Abstract

Climate change requires transforming the production processes of high-emission industries toward low-carbon technologies. One of the main emitters of greenhouse gases is the steel industry. Therefore, steel manufacturers are planning to substitute the blast furnace-basic oxygen furnace route with hydrogen-based direct reduction and electric arc furnaces. Thus, direct greenhouse gas emissions can be avoided almost entirely. This involves changes in the materials and energies used. Besides hydrogen, natural gas is becoming more important for the direct reduction of iron ores. Therefore, future greenhouse gas emissions associated with low-carbon steelmaking are deeply intertwined with the developments of the system environment. Upon potential transformation pathways of the system environment, future greenhouse gas emissions from natural gas and hydrogen-based direct reduction coupled with electric arc furnaces are investigated. To this end, a prospective cradle-to-gate life cycle assessment approach is used. The results indicate that greenhouse gas emissions highly depend on the electricity mix if hydrogen is produced by electrolysis. Using natural gas for direct reduction is a viable short-term option until the decarbonization of the energy sector is further advanced.

Keywords: Life cycle assessment; Crude steel production; Direct reduction-electric arc furnace route; Decarbonization; Transformation

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1. Introduction

Due to climate change, it is required to decarbonize high-emission industries such as the steel industry. Approximately 7% of global greenhouse gas (GHG) emissions result from steelmaking processes, especially from primary steelmaking [1]. In most cases, the coal-based blast furnace-basic oxygen furnace (BF-BOF) route is used for the primary production of crude steel [2]. However, alternative technologies for reducing direct GHG emissions of steelmaking already exist. As of today, most steel manufacturers are planning to substitute BF-BOF production facilities with direct reduction plants (DRP) and electric arc furnaces (EAF) from 2025 onwards [3–5]. In this process design, sponge iron is produced within the DRP. Afterward, the sponge iron is further processed within the EAF for crude steel production. Existing DRPs are currently solely operated with natural gas (NG/DR) for direct reduction [1]. The NG/DR-EAF process serves as a transitional technology in the transformation process of integrated steel mills toward low-carbon steelmaking. In the long term, NG/DR can be substituted by hydrogen-based direct reduction (H/DR) of iron ore. If hydrogen is used, direct GHG emissions can be reduced by up to 97% [6]. A framework for designing economically advantageous transformation pathways is developed within [7].

However, indirect GHG emissions highly depend on the way the hydrogen is produced. To reduce the overall GHG emission intensities as much as possible, producing hydrogen by electrolysis is required [8]. Thus, emissions from hydrogen production highly depend on the electricity mix. The future development of the electricity mix of different countries is highly uncertain. Therefore, steel manufacturers are starting to invest in their own facilities for electricity production aiming to operate hydrogen production served by their renewable energy [9]. Furthermore, cooperations with energy suppliers for the

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provision of electricity from renewable energy sources for hydrogen production are conceivable.

The environmental impact of primary steelmaking via the BF-BOF route has been investigated in-depth in previous research [10–13]. Further studies focus on historical and future GHG emissions of primary and secondary steelmaking. However, novel processes, such as the use of hydrogen for direct reduction, are not included [14]. Also, resulting GHG emissions are often reported in an aggregated manner for different steelmaking technologies [15]. So far, only a few studies investigated the environmental impact of steelmaking via the direct reduction-electric arc furnace (DR-EAF) route. Moreover, these studies mainly focus on direct GHG emissions of steelmaking processes. To this end, the resulting GHG emissions from steelmaking are calculated from average input quantities and carbon fractions of reduction agents and fuels [16,17] or based on flowsheet simulation models [8]. Other studies include the GHG emissions from electricity generation within the investigated countries. Thus, besides direct GHG emissions, solely indirect GHG emissions from electricity generation are considered [18,19]. Upstream GHG emissions from the extraction, processing, and transport of raw materials are neglected. Further limitations in previous research refer to future developments of the system environment. So far, exclusively future changes in the electricity mix are included [18,19]. The comprehensive inclusion of potential developments within the system environment concerning other sectors, such as transportation, is not addressed.

Overall, steel manufacturers need to be further supported in evaluating the climate impact of substituting natural gas and hydrogen within the DR-EAF route, allowing for a changing system environment. To comprehensively assess the climate impact of DR-EAF steelmaking, indirect GHG emissions must be included for all related sectors besides direct GHG emissions.

To this end, we conduct a (prospective) environmental life cycle assessment (LCA) for H/DR-EAF and NG/DR-EAF steelmaking. Thus, potential future developments of the environment, e.g., the energy or transport sector, are included. The time span between 2025 and 2040 is investigated. Within the H/DR-EAF route, we distinguish between hydrogen produced by polymer electrolyte membrane (PEM) electrolysis with electricity from the German grid mix and electricity from onshore wind turbines. To this end, we model the material and energy flows of DR-EAF steelmaking based on literature data. The main contribution of this article is as follows: On the example of NG/DR-EAF, and H/DR-EAF routes, the climate impact of primary steelmaking in the medium term is examined. This enables steel manufacturers to evaluate the impact of substituting natural gas with hydrogen for direct reduction within the early phase of the transformation process. Also, the potential for GHG emission reductions in the case of exclusively using hydrogen from PEM electrolysis with wind-generated electricity is quantified.

2. Methods

This study aims to quantify the climate impact of DR-EAF steelmaking differentiating between NG/DR and H/DR. Thus, the remainder of this study is leaned on the framework for environmental LCA provided within ISO 14040:2006 [20]. To ensure consistency with previous studies, the guidelines of the World Steel Association are considered [21].

2.1 Goal and scope definition

Since indirect GHG emissions highly depend on the region the investigated steel mill is located, the assessment within this study focuses on Germany. An annual crude steel production of 1 ton between 2025 and 2040 is defined as a functional unit. A cradle-to-gate approach is used for LCA, including the environmental impacts from raw material extraction to crude steel production. The environmental impacts of downstream processes and the use phase are excluded.

Within the production facilities of the DR-EAF route, material and energy flows (Fig. 1) of the unit processes are modeled using activity analysis [22]. Changes in the system environment are considered by a prospective LCA approach, including different future developments of the background system.

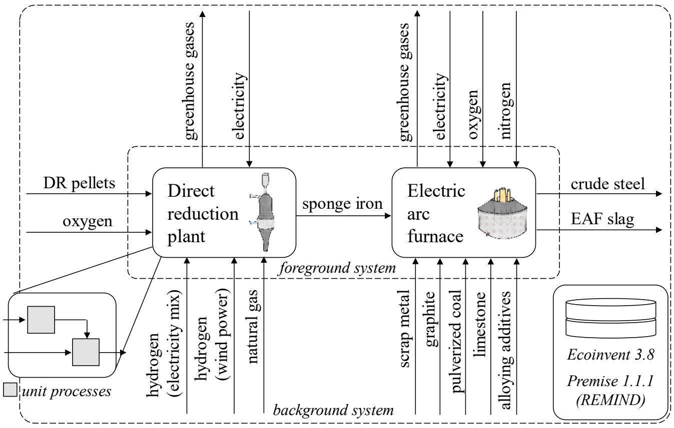

Fig. 1. Simplified material and energy flows within the system boundaries of DR-EAF steelmaking.

2.2 Life cycle inventory analysis

For life cycle inventory analysis, crude steel production processes via the DR-EAF route are modeled based on literature data. Both, data from flowsheet simulations [23] and industry data [24] are used. Therefore, it is distinguished between three process designs. In process 1, NG/DR is assumed. Process 2 considers H/DR with hydrogen produced by PEM electrolysis with the German electricity mix. In process 3, hydrogen is produced by PEM electrolysis with electricity from onshore wind turbines. Process-specific input and output quantities of the main materials and energies are derived from flowsheet simulation models. These datasets are extended by literature data on EAF-steelmaking to allow for a comprehensive life cycle impact assessment. Transportation of the produced hydrogen and natural gas by pipeline is assumed in all cases. For hydrogen supply, an average transport distance of 300 kilometers within Germany is assumed. Countries of origin and transport distances for natural gas supply are derived from *Ecoinvent 3.8* [25]. The material and energy flows within the system boundaries of this research work are given in Table 1.

Thereby, negative values indicate inputs and positive values indicate outputs. Within Table 1, material and energy flows are normalized to the production of one ton of sponge iron in the DRP as well as one ton of crude steel in the EAF.

Table 1. Input/output quantities of material and energy flows.

	Material and energy flows	Process 1	Process 2	Process 3
DRP	DR pellets [t]	-1.36	-1.39	-1.39
	Hydrogen (German electricity mix) [GJ]	-	-7.96	-
	Hydrogen (wind power) [GJ]	-	-	-7.96
	Natural gas [GJ]	-10.09	-	-
	Electricity [MWh]	-0.08	-0.087	-0.087
	Oxygen [Nm^3]	-59.86	-	-
	Sponge iron [t]	1	1	1
EAF	Sponge iron [t]	-0.98	-0.911	-0.911
	Scrap metal [t]	-0.173	-0.161	-0.161
	Graphite [t]	-0.004	-0.004	-0.004
	Pulverized coal [t]	-	-0.01	-0.01
	Limestone [t]	-0.08	-0.08	-0.08
	Alloying additives [t]	-0.017	-0.017	-0.017
	Electricity [MWh]	-0.474	-0.524	-0.524
	Oxygen [Nm^3]	-40.6	-2.9	-2.9
	Nitrogen [Nm^3]	-6.4	-6.4	-6.4
	EAF slag [t]	0.165	0.117	0.117
	Crude steel [t]	1	1	1

In all three scenarios, a scrap input rate of 15% is assumed. The main iron fraction (85%) is fed into the EAF in the form of sponge iron. In line with previous research [11,16,17] and reporting standards [21,26], direct GHG emissions from processes within the DRP and EAF are calculated based on the carbon contained within the input and output materials and energies. Complete combustion processes are assumed within the DRP and EAF. Hence, solely carbon dioxide emissions result depending on carbon input quantities. To calculate resulting carbon dioxide emissions, the following factor is used considering the molecular masses of carbon (M_C) and carbon dioxide (M_{CO2}): $M_{CO2}/M_C=3.664$. Carbon fractions within the input materials and energies are derived from literature. Sponge iron produced by H/DR is assumed to have a carbon fraction of 4.6 kg/ton. If sponge iron is produced with NG/DR, the carbon fraction (13.7 kg/ton) is higher [16]. For pulverized coal, a carbon fraction of 800 kg/ton [27], for limestone 110 kg/ton, and for crude steel 0.4 kg/ton [17] is assumed. Based on the average natural gas composition in Europe [28], a carbon fraction of 14.7 kg/GJ is calculated. Thus, direct GHG emissions resulting from the oxidation of reducing agents and the removal of carbon from the main input materials are considered.

Indirect GHG emissions from the extraction and transport of raw materials and energies are identified using the *Ecoinvent 3.8 cut-off database* [25], *Premise 1.1.1* [29], and *REMIND scenarios* [30]. To this end, the scenarios SSP2-PkBudg900, SSP2-PkBudg1300, and SSP2-Base from *Premise* are included. These scenarios correspond to an expected increase of the global atmospheric temperature by 1.5°C (SSP2-PkBudg900), 2°C (SSP2-PkBudg1300), and 3.5°C (SSP2-Base) until 2100 compared to pre-industrial levels [31].

Indirect GHG emissions consist of upstream and credit emissions. Upstream emissions result from electricity generation or raw material extraction, processing, and transport. Credits are included for by-products that substitute raw materials or energies in other industries, such as EAF slag [21,32].

Countries of origin of raw materials and energies are based on industry and import data. Transport distances are adjusted accordingly. For raw materials, transport by train within the countries of origin is assumed. The materials are then assumed to be shipped by a bulk carrier to Germany. There, they are transported by train and barge since most integrated steel mills are connected to the rail network and located at a river.

2.3 Life cycle impact assessment

Global warming potential (GWP) is used as a midpoint indicator, with the impact category IPCC 2013, climate change, GWP100a. Thus, the climate impact of DR-EAF production is quantified. Based on the illustrated life cycle inventory and impact assessment, the GHG emission intensities of producing 1 ton of crude steel per year between 2025 and 2040 are investigated. In total, nine scenarios are included. These scenarios result from combining three DR-EAF route process designs with three potential future developments of the system environment (Fig. 2). To this end, individual databases are created for each year within the investigated time span as well as for all scenarios regarding the system environment development.

3. Results and discussion

Overall GHG emission intensities range between 0.83–1.04/0.86–1.09/1.07–1.18 $t_{CO2\text{-}eq}/t_{crude\ steel}$ in the scenarios SSP2-PkBudg900/SSP2-PkBudg1300/SSP2-Base for crude steel production through the NG/DR-EAF route. Thus, GHG emission intensities only slightly depend on future developments of the system environment. GHG emission intensities of the H/DR-EAF route depend heavily on whether hydrogen is produced with the German electricity mix or with electricity from wind turbines. In the scenarios SSP2-PkBudg900/SSP2-PkBudg1300/SSP2-Base, overall GHG emission intensities range between 0.39–1.12/0.45–1.32/1.24–

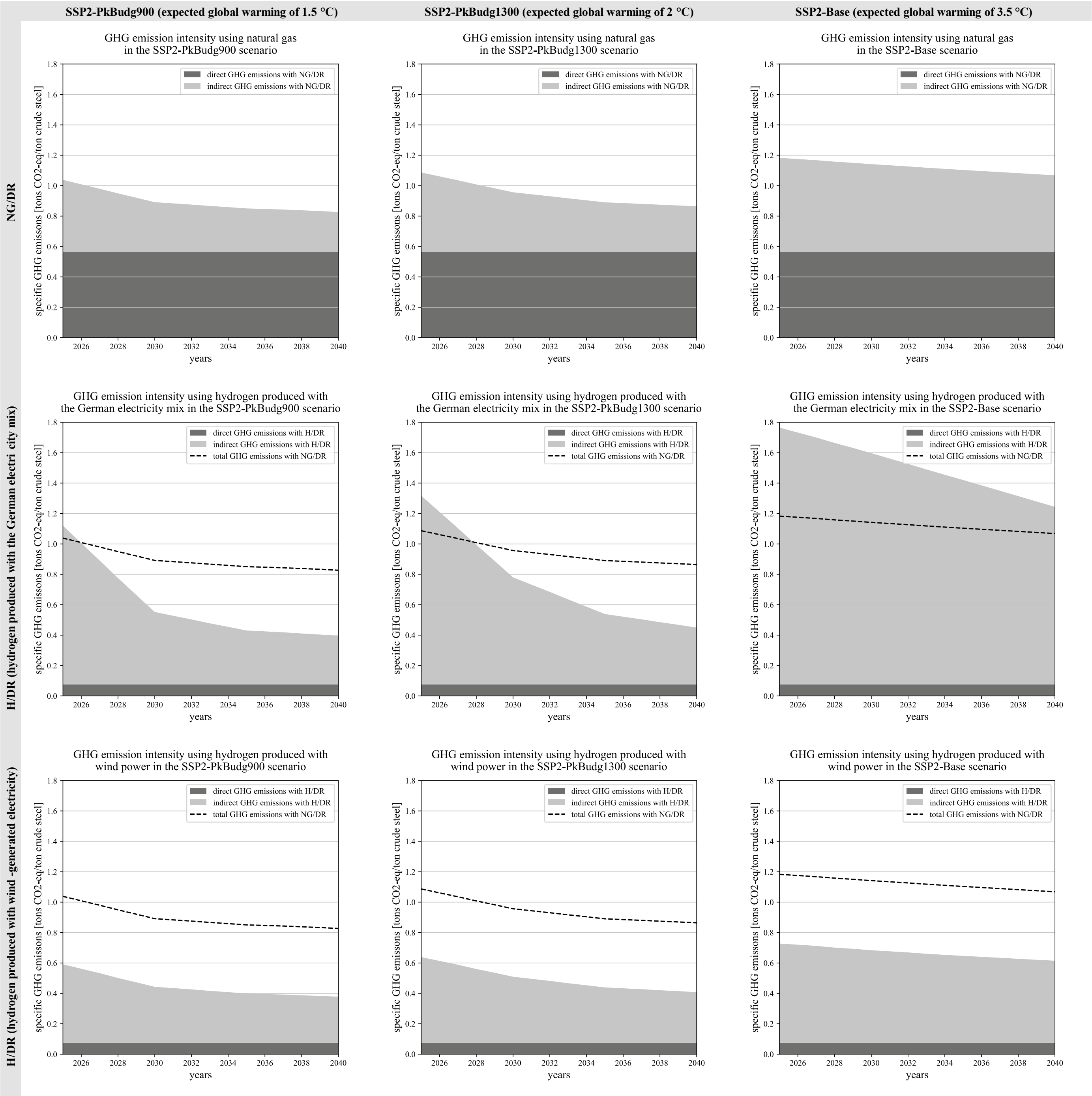

Fig. 2. GHG emission intensities of crude steel production by the DR-EAF route considering different scenarios regarding DRP operation and system environment developments.

1.76 $t_{CO2\text{-}eq}/t_{crude\ steel}$ if hydrogen is produced by PEM electrolysis with the German electricity mix. If electricity from onshore wind turbines is used instead, GHG emission intensities are reduced to 0.38–0.59/0.41–0.64/0.61–0.73 $t_{CO2\text{-}eq}/t_{crude\ steel}$.

Direct GHG emissions from steelmaking do not change throughout the investigated time span. This is because no technical process improvements within the production facilities of the integrated steel mill are assumed. However, direct GHG emissions from NG/DR-EAF production (0.565 $t_{CO2\text{-}eq}/t_{crude\ steel}$) are significantly higher compared to direct GHG emissions from H/DR-EAF steelmaking (0.076 $t_{CO2\text{-}eq}/t_{crude\ steel}$). These results are in line with previous research [8,16]. Thus, using hydrogen instead of natural gas is favorable to minimize the direct GHG emissions from steelmaking. Besides the ecological aspect, this is very relevant for steel manufacturers from an economic point of view, as costs arise for these emissions within the European Union Emissions Trading System (EU-ETS) [33]. However, for both NG/DR and H/DR-based crude steel production, direct GHG emission intensities are reduced compared to the BF-BOF route which results in direct GHG emissions of 1.7–1.9 $t_{CO2\text{-}eq}/t_{crude\ steel}$ [12,34].

Lower indirect GHG emissions result from NG/DR-EAF production compared to H/DR-EAF steelmaking. First, less electricity is needed for NG/DR-EAF production within the integrated steel mill and upstream processes [23]. Thus, future developments in the system environment also have a smaller impact on indirect GHG emissions resulting from NG/DR-EAF steelmaking. Second, credits are included for EAF slag. In the NG/DR-EAF route, more EAF slag is produced compared to the H/DR-EAF route. This slag is assumed to be provided to other industries, substituting the use of raw materials in these sectors [21]. This exceeds the impact caused by a slightly higher amount of pellets used compared to the H/DR-EAF route.

In the case of H/DR using hydrogen produced by PEM electrolysis with the German electricity mix, indirect GHG emissions are significantly influenced by developments of the system environment. H/DR is environmentally favorable compared to NG/DR in the SSP2-PkBudg900 scenario from 2026 onwards. In the SSP2-PkBudg1300 scenario, H/DR is favorable from 2028 onwards. The results underline that the short-term use of NG/DR is acceptable from an environmental perspective. However, hydrogen production capacities and transport infrastructure need to be built up fast to enable the medium-term transition toward H/DR.

In case of a pessimistic view on future developments of the system environment (SSP2-Base), H/DR leads to higher overall GHG emissions compared to NG/DR throughout the investigated time span. Within this scenario, very slow decarbonization of the energy sector is assumed. Although this is not a likely outcome considering the current policies of the German government [35] as well as the European Union [36], this scenario does highlight the need for fast decarbonization of the energy sector.

If hydrogen is produced by PEM electrolysis with electricity from wind turbines instead, H/DR has a lower GHG emission intensity compared to NG/DR in all scenarios between 2025 and 2040. This underlines that early investment by steel manufacturers in electrolyzers, as well as low-emission electricity production facilities, are of high importance for the fast decarbonization of the steel industry. To this end, policy measures that provide support in the form of subsidies could be of assistance.

For all included future developments of the system environment, the average GHG emissions intensities are the lowest, if H/DR is applied with hydrogen produced by PEM electrolysis from wind power (Table 2). Using hydrogen produced with the German electricity mix is only reasonable once the decarbonization of the energy sector has progressed further. This is particularly evident in the scenario SSP2-Base, where average GHG emission intensities throughout the investigated time span are significantly higher compared to NG/DR-EAF steelmaking.

Table 2. Average annual GHG emission intensities between 2025 and 2040 in $t_{CO2-eq}/t_{crude\ steel}$.

	REMIND SSP2-PkBudg900	REMIND SSP2-PkBudg1300	REMIND SSP2-Base
Process 1	0.591	0.744	1.507
Process 2	0.445	0.493	0.668
Process 3	0.894	0.943	1.124

4. Conclusion

Most European steel manufacturers are planning to transform their integrated steel mills' production infrastructure toward DR-EAF production to significantly reduce GHG emissions from primary steelmaking. This article consists of a prospective cradle-to-gate LCA approach for DR-EAF steelmaking. For environmental impact assessment, it is differentiated between NG/DR, H/DR with hydrogen from electrolysis using the German electricity mix, and H/DR with hydrogen from electrolysis using electricity from onshore wind turbines. The developed assessment provides an understanding of the environmental impacts of the DR-EAF route considering different future developments of the system environment.

This study finds that direct GHG emissions can be reduced by around 96% if H/DR-EAF production is applied to substitute the BF-BOF route. However, indirect GHG emissions are highly intertwined with future developments of the system environment. Thus, fast decarbonization of the energy sector is highly important to heavily reduce overall GHG emissions. Also, GHG emissions from raw material extraction, processing, and transportation need to be reduced to aim for a low GHG emission steel industry. Process-related, direct GHG emissions are higher when NG/DR is applied. Indirect emissions, however, are less affected by system environment developments. Thus, natural gas provides a viable short-term option for the DR process. Besides decarbonization of the system environment which needs to be driven by policymakers, steel manufacturers need to focus on measures to increase their shares of low-carbon hydrogen in the early phase of the transformation process. To this end, electrolysis capacities need to be installed if sufficient external hydrogen sources for H/DR are not available. Also, increasing the share of low-carbon electricity to operate electrolysis facilities is of high importance.

In our study, simulation data for NG/DR-EAF and H/DR-EAF steelmaking is complemented by data from the steelmaking practice. As the adoption of technologies for low-carbon steelmaking increases, more comprehensive simulation data or primary datasets can be used within future LCA studies. Also, it is only differentiated between two scenarios for hydrogen production by PEM electrolysis in our study. The impact assessment focuses solely on Germany. Secondary steelmaking and increasing returns of scrap throughout the investigated time span are neglected. A more comprehensive LCA including multiple scenarios for hydrogen production and sourcing might be conducted in future research. Also, the impact of different regional environmental conditions on the indirect GHG emissions of the integrated steel mill can be further analyzed. To holistically evaluate the environmental impact of DR-EAF steelmaking, additional impact categories can be included.

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