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# Prospective assessment of transformation pathways toward low-carbon steelmaking: Evaluating economic and climate impacts in Germany

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ABSTRACT

Due to climate change, there is an urgent need to decarbonize high-emission industries. As coal-based operations predominate in primary steelmaking, the steel industry offers an exceptionally high potential for reducing greenhouse gas emissions. Alternative processes for almost fully decarbonized primary steelmaking exist but require substantial investments by steelmakers for their implementation while maintaining desired production levels during the transformation periods. In this context, the energy carriers required change such that the transformation of the steelmaking processes is deeply intertwined with the transformation of the background system. For the first time, we evaluate potential transformation pathways from the steelmakers' perspective using a prospective life cycle assessment approach. We find that hydrogen may facilitate a reduction of direct emissions by around 96 % compared to conventional steelmaking in 2050. However, indirect emissions remain at a high level throughout the transformation period unless the upstream stages of the value chain are transformed accordingly.

## 1. Introduction

Climate change is an existential threat to global society, demanding an urgent reduction in high-emission anthropogenic activities in all sectors (European Commission, 2021). As one of the main contributors, the steel industry accounts for around 7 % of total emissions from the energy system due to the sector's high reliance on coal-based energy inputs for primary steelmaking (International Energy Agency, 2020). As an alternative to primary steelmaking, scrap-based secondary steelmaking leads to significantly lower climate impacts. However, due to the limited availability of scrap metal, this route has a global share of only 30 % (World Steel Association, 2022). Consequently, besides enhancing scrap-based secondary steelmaking, initiatives worldwide emphasize the relevance of low-carbon processes and the related alternative technologies to reduce the greenhouse gas (GHG) emissions from primary steelmaking (Quader et al., 2015). Major steelmakers are picking up on this and show readiness for transforming their facilities. The currently predominant route in primary steelmaking comprising blast furnaces (BF) and basic oxygen furnaces (BOF) in integrated steel mills is therefore envisaged to be replaced by a direct reduction (DR) of iron ore using hydrogen (H/DR) and electric arc furnaces (EAF) expecting a relative reduction of over 90 % of direct carbon dioxide emissions (Salzgitter, 2022a; SSAB et al., 2021; Thyssenkrupp, 2022).

However, replacing BF-BOF processes is challenging. DR-EAF production requires new energy sources, especially electricity, natural gas, and hydrogen. Additionally, higher-quality raw materials are required, particularly in terms of pellets for DR processes (Doyle and Voet, 2021). This leads to price premiums compared to conventional raw materials. Also, steelmaking is determined by long-lived assets where half of the global production capacity may not have reached half of its economic life (International Energy Agency, 2019; Vogl et al., 2021). Steelmakers willing to transform their facilities from BF-BOF to H/DR-EAF, therefore, face early replacement investments of a substantial extent combined with significant efforts for the engineering and implementation of the new facilities and the associated supply chains. Consequently, steelmakers aim to transform their facilities over several decades while maintaining desired production volumes rather than suddenly changing their processes (Salzgitter, 2022a; SSAB et al., 2021; Thyssenkrupp, 2022).

The long-term planning horizon imposes several challenges for steelmakers in correctly evaluating alternative transformation pathways' environmental and economic impacts. First, *interdependencies of material and energy flows between the routes* require detailed consideration as the routes are operated in parallel for several years during the

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transformation. Besides others, this is particularly relevant for the highly energetic process gases occurring in BF-BOF, which are used for electricity generation in integrated steel mills. With a stepwise shift of production volume to H/DR-EAF, steelmakers face a decrease in electricity generation and increased demand for electricity in the new route (Fischedick et al., 2014). Therefore, material and energy flows within and between the routes must be considered in detail. Second, the *anticipation of short-term decisions* is required to assess transformation pathways as steelmakers will economically utilize the given capacities each year. This applies across routes, i.e., steelmakers decide on the individual production volume of the facilities in BF-BOF and H/DR-EAF. However, this also applies within routes, e.g., steelmakers may substitute hydrogen with natural gas in the facilities for direct reduction of iron ore (NG/DR). Consequently, steelmakers use short-term flexibility to respond to market conditions, which may significantly affect the economic and environmental assessment of the processes. Therefore, the steelmakers' short-term economic behavior must be reflected in the long-term assessment of transformation pathways. Third, the *transformation of interrelated sectors* has to be considered, as their decarbonization affects the impact of steelmaking. This is particularly relevant for changes in the energy sector as the high emissions reduction potential in H/DR-EAF is specified for electricity generation and hydrogen production exclusively from renewable energy sources. This is not likely to apply to most countries within the following years, as the energy sector is the subject of a transformation itself. Consequently, the environmental impact of steelmaking strongly interdepends with the transformation of interrelated sectors. Therefore, a prospective assessment approach integrating the stages of the value chain facilitates the environmental and economic assessment of steelmaking during the decades of transformation. Fourth, the *development of steel demand in future decades* must be considered. Motivating their transformation, steelmakers particularly emphasize the higher eco-efficiency of H/DR-EAF processes (e.g., less $t_{CO2\text{-}eq}/t_{crude\ steel}$). However, as the global demand for steel from primary steelmaking is projected to increase in the future (International Energy Agency, 2020; Wang et al., 2021), an increase in steelmakers' production volumes may counteract the efficiency gains. Therefore, the impact assessment is required to address indicators of eco-effectiveness besides eco-efficiency to facilitate insights into the absolute contribution of steelmakers.

Literature on transforming steelmaking processes does not sufficiently reflect these challenges. First, research focuses on the *environmental impact assessment of established technologies* for primary steelmaking. These articles serve to illustrate the complex interdependencies between facilities in integrated steel mills, however, merely considering established technology and neglecting the transformation toward alternative technologies (Backes et al., 2021; Burchart-Korol, 2013; Li et al., 2018; Olmez et al., 2016; Renzulli et al., 2016; Suer et al., 2021). Second, researchers tackle *the environmental and economic impact assessment of alternative technologies* for steelmaking. Those approaches predominantly consider static environments, i.e., certain initial and potential future states are assessed irrespective of potential pathways between them. The findings serve steelmakers in defining suitable (potentially intermediate) technological targets for their transformation. However, the dynamic nature of transformation is neglected regarding the interdependencies occurring between and within routes and interrelated sectors impeding steelmakers' assessment of reasonable transformation pathways (Bhaskar et al., 2022; Chisalita et al., 2019; Fan and Friedmann, 2021; Fischedick et al., 2014; Gielen et al., 2020; Graupner et al., 2023; Jacobasch et al., 2021; Krüger et al., 2020; Müller et al., 2021; Nurdiawati et al., 2023; Rechberger et al., 2020; Suer et al., 2022; Vogl et al., 2018; Yang et al., 2021; Yilmaz and Turek, 2017). Third, mainly from the environmental perspective, researchers assess *future demand developments and technological scenarios* in the steel industry, considering the developments in interrelated sectors. Those approaches predominantly consider a dynamic environment, i.e., different technologies are evaluated over time. The findings may serve policymakers in defining reasonable sustainability targets for the considered sectors. However, the economically oriented behavior of steelmakers and interdependencies within and between routes lack sufficient consideration (de Souza and Pacca, 2023; Morfeldt et al., 2015; Radloff et al., 2023; Ryberg et al., 2018; van Ruijven et al., 2016; Wang et al., 2021, 2018, 2017; Yellishetty et al., 2010). Fourth, researchers assess *potential transformation pathways of the entire steel industry* of specific regions. However, interdependencies between different routes that occur during the transformation of individual steel mills are neglected. In addition, dynamic changes in the environment that affect upstream GHG emissions are not fully considered. For the environmental assessment, only a change in the countries' electricity mix over time is included. Previous research examined a transformation of the steel industries in Northwestern Europe and Brazil (Arens et al., 2017; Hebeda et al., 2023; Pinto et al., 2018; Schneider, 2022; Toktarova et al., 2020). The results from these studies can help policymakers evaluate the impact of different transformation pathways on the entire steel industry. However, steelmakers cannot evaluate the environmental and economic impacts of alternative transformation pathways of individual integrated steel mills.

The main contribution of this article is as follows: For the first time, on the example of BF-BOF, H/DR-EAF, and NG/DR-EAF routes, the dynamic nature of transforming primary steelmaking in integrated steel mills is examined for alternative pathways. To this end, the interdependencies of material and energy flows within and between the routes, anticipation of short-term decisions, the transformation of interrelated sectors, and the development of steel demand are considered in an interdisciplinary approach combining life cycle engineering, business economics, and operations research. By including upstream processes in the life cycle assessment, direct and indirect climate impacts resulting from transformation scenarios are reported. This will support steelmakers in evaluating potential transformation pathways of integrated steel mills economically and environmentally.

## 2. Methods

This study consists of a prospective approach for the environmental life cycle assessment (LCA) (International Standard ISO 14040, 2006) and economic impact assessment. For the life cycle inventory analysis, we model the material and energy flows of BF-BOF, H/DR-EAF, and NG/DR-EAF routes, explicitly considering the interdependencies within and between the routes. The modeling of material and energy flows is based on activity analysis (Koopmanns, 1951) and linked with linear programming (Dantzig, 1968) to anticipate steelmakers' short-term decisions for given production capacities (Fig. 1a). Additionally, scenarios regarding the future development of interrelated sectors are included based on the REMIND model (Luderer et al., 2020). Thus, we can environmentally and economically assess alternative transformation pathways toward low-carbon steelmaking processes in integrated steel mills.

### 2.1. Goal and scope

The steel industry emits substantial amounts of GHG, which must be reduced economically to avoid production relocations to other regions. To this end, the environmental assessment focuses on the impacts on climate change. The economic assessment includes cash outflows and costs resulting from steelmaking activities. Further environmental or socio-economic impacts required to assess the sustainability of steelmaking transformation pathways holistically are not included (Hertwich et al., 2015; Hottenroth et al., 2022). Thus, our analysis aims to quantify tradeoffs between cost increases and GHG emission reductions rather than evaluating the overall sustainability of transformation scenarios.

In steelmaking, emissions and costs are highly affected by the considered geographic region (Hasanbeigi et al., 2016). We specify our

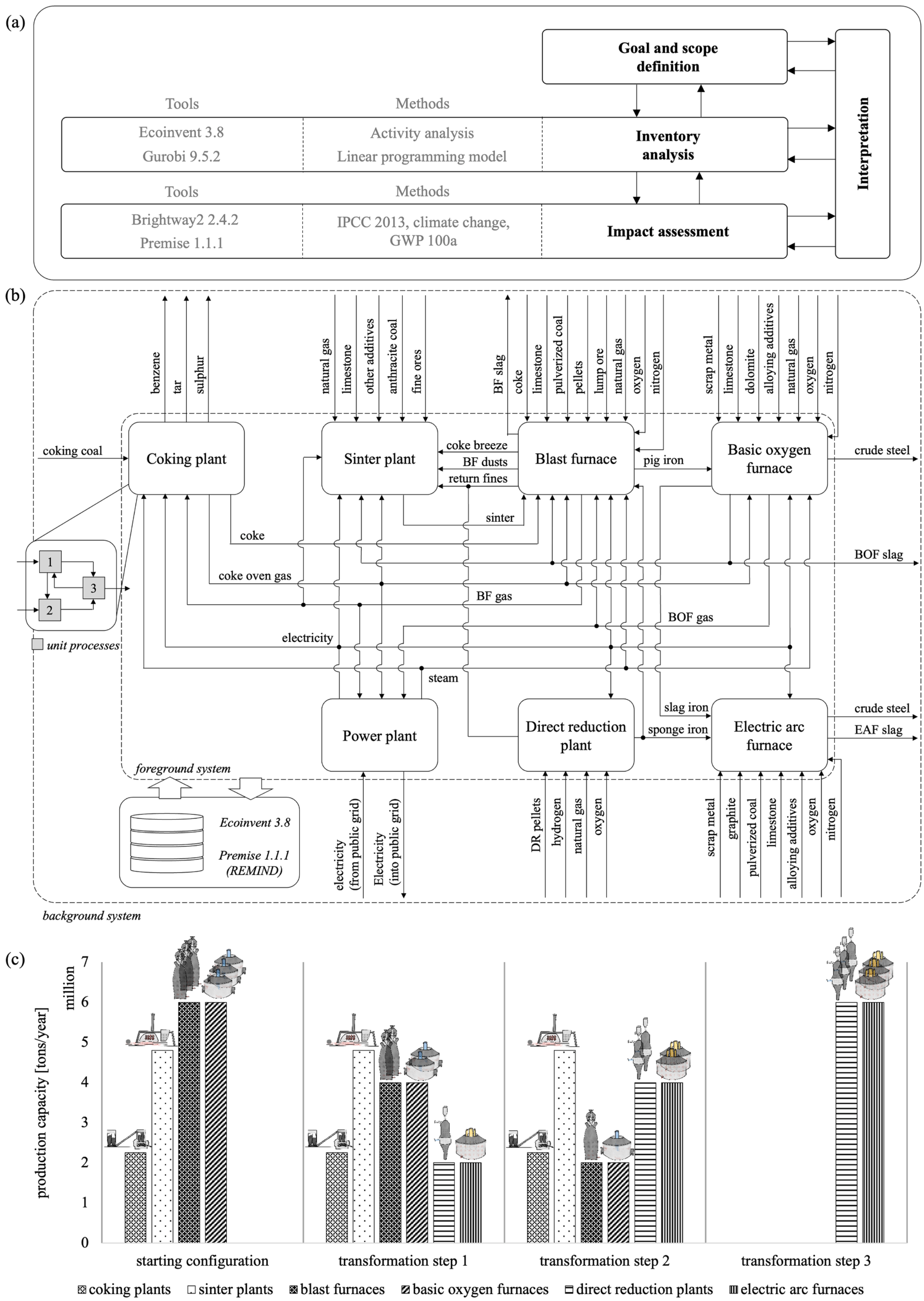


**Fig. 1.** (a) Life cycle assessment framework according to ISO 14040 and the main tools and methods used within the steps. (b) System boundaries of the analyzed system with simplified energy and material flows. (c) Several transformation pathways are considered in this article, varying in the capacities of available facilities and processes over time within three transformation steps.

assessment for Germany as the origin of most European steel. To investigate potential transformation pathways (Fig. 1c), different plant configurations and production quantities are defined based on data from existing European steel mills (Eurofer, 2020). On the one hand, focusing on eco-efficiency, we use a constant annual production quantity of 6, 000,000 $t_{crude\ steel}$/year between 2022 and 2050 as a functional unit. On the other hand, focusing on eco-effectiveness, the annual production volumes reflect the projected advent of primary steelmaking based on global forecasts. For crude steel production, facilities and processes of BF-BOF, H/DR-EAF, and NG/DR-EAF routes are differentiated. Therefore, several unit processes in the production facilities are modeled using activity analysis (Fig. 1b).

The boundaries of the analyzed foreground system contain the processes for crude steel production. Downstream production areas, e.g., the rolling mill or surface finishing, are not included, as any transformation plans exclusively affect the metallurgical and upstream processes. Thus, the impacts of downstream steelmaking processes and the use phase are excluded. As a result, a cradle-to-gate approach is used for LCA in this study in which all impacts from the extraction of raw materials to the production of crude steel are included. For the economic assessment, a gate-to-gate approach is used. Thus, costs for consumed materials and energies within the integrated steel mill are included. Also, capital costs and other operational costs are considered. A prospective approach considers the projected changes in economic and climate impacts over time.

### 2.2. Life cycle inventory analysis

Material and energy flows of BF-BOF steelmaking are quantified based on real data from the steelmaking industry (Bhattacharya and Muthusamy, 2017; Remus et al., 2013) as well as process simulations (Yilmaz and Turek, 2017). Average input and output values are used for material and energy flows originating from integrated steel mills within the European Union. Thus, we aim to depict the processes of a typical European integrated steel mill. For the BF-BOF route, it is assumed that all generated by-product gases are either consumed as fuel gases within the production facilities for crude steel production or to produce electricity and steam within the power plant. As H/DR processes combined with EAF steelmaking are not yet operated at an industrial scale, material and energy flows are mainly based on process simulations (Jacobasch et al., 2021; Müller et al., 2021). These datasets are extended by real data, e.g., from the NG/DR process or scrap-based EAF steelmaking (Remus et al., 2013). A shaft furnace design of the DRP is assumed in this study. This allows for a flexible use of natural gas or hydrogen for direct reduction. In both routes, a scrap input rate of 15 % is assumed.

Production facilities for steelmaking consist of multiple unit processes modeled using activity analysis. As crude steel can be provided using different unit processes during the transformation, the life cycle inventory levels depend on the steelmakers' decisions in the short term (Graupner et al., 2022). We use a linear programming model to evaluate each year's life cycle inventory levels, thus considering the interdependencies of material and energy flows between the routes. The model aims to minimize the annual variable costs of crude steel production. The development of annual capital costs and other operational costs is predefined as given transformation pathways are analyzed. The model includes capacity and process constraints to obtain valid life cycle inventory levels. It is implemented in *Python 3.9.12* and solved using *Gurobi 9.5.2*. The mathematical formulation and a more detailed description of the model are provided in the supplementary material.

Further, assumptions on BF-BOF and DR-EAF steelmaking production facilities are needed (Table 1). Capacities and economic lifetimes are based on industry data and previous research works. For newly installed production facilities, an economic lifetime of 25 years is assumed (Babich and Senk, 2015; Bhaskar et al., 2022; Hooey et al., 2013; Jacobasch et al., 2021; Kuramochi et al., 2012; Remus et al., 2013; Wortler et al., 2013; Yang et al., 2021). Capital costs and other operational costs of production facilities are derived from previous studies (European Commission, 2015; Hooey et al., 2013; Wortler et al., 2013). To determine crude steel costs, we assume that existing plants have already been fully depreciated upon the start of the transformation process.

**Table 1**
Technical and economic parameters of included production facilities. Economic parameters refer to the baseline year 2022.

| Production facilities | Capacities | Investments | Other operational costs |
|---|---|---|---|
| Coking plant | 2.25m $t_{coke}$/year | / | 54.4m $EUR_{2022}$/year |
| Sinter plant | 4.8m $t_{sinter}$/year | / | 22.1m $EUR_{2022}$/year |
| Blast furnace | 2m $t_{pig\ iron}$/year | / | 33.2m $EUR_{2022}$/year |
| Basic oxygen furnace | 2m $t_{crude\ steel}$/year | / | 57.5m $EUR_{2022}$/year |
| Direct reduction plant | 2m $t_{sponge\ iron}$/year | 583.4m $EUR_{2022}$ | 32.2m $EUR_{2022}$/year |
| Electric arc furnace | 2m $t_{crude\ steel}$/year | 466.7m $EUR_{2022}$ | 85.1m $EUR_{2022}$/year |
| Power plant | 4.5 $TWh_{electricity}$/year | / | 20.7m $EUR_{2022}$/year |

Variable production costs associated with using materials and energies are based on market data. A price premium of 10 % is included for high-quality pellets compared to conventional iron ore (Doyle and Voet, 2021; Fischedick et al., 2014). For the future costs of electricity and hydrogen, individual cost projections are included (Federal Ministry for Economic Affairs and Climate Action, 2022a, 2022b) due to the ongoing transformation of the energy system as well as the ramp-up of hydrogen production and transportation infrastructure. Due to high uncertainty, we conduct sensitivity analyses on the major energy cost trajectories. All cost parameters are adjusted by inflation to the reference year 2022.

To quantify the GHG emissions associated with the execution of steelmaking activities, direct and indirect emissions need to be distinguished. Direct GHG emissions from primary steelmaking processes almost solely consist of carbon dioxide emissions due to complete combustion. In line with previous research, indirect emissions are divided into upstream emissions and credits (World Steel Association, 2011). Upstream emissions occur, among others, from raw materials mining and transport and electricity consumption. Environmental credits are mainly due to the production of electricity and the provision of by-products to other industries (Backes et al., 2021; Suer et al., 2021).

Direct carbon dioxide emissions are calculated based on stoichiometry. To this end, two approaches are used. First, literature-based values from existing integrated steel mills are used to specify the composition of process gases of the coking plant, BF, and BOF (Bhattacharya and Muthusamy, 2017; Remus et al., 2013). Due to the complete combustion of these gases in either the production facilities or the power plant, all contained carbon leads to carbon dioxide emissions. Second, direct emissions are calculated based on the difference between the carbon contained in the input and output materials in production facilities that are not producing process gases. The carbon contents of different input and output materials are mainly derived from previous research works (Iosif et al., 2008; Müller et al., 2021; U.S. Energy Information Administration, 2022; Yang et al., 2021; Yilmaz and Turek, 2017). This approach is used for the sinter plant, DR plant, and EAF. Since no technical improvements to existing plants are considered in this study, direct carbon dioxide emissions do not change throughout the transformation if the same materials and energies are used.

To identify upstream emissions and credits, datasets from the *Ecoinvent 3.8* cut-off database (Wernet et al., 2016) combined with *Premise 1.1.1* (Sacchi et al., 2022) are used via *Brightway2 2.4.2* (Mutel, 2017). Therefore, all input and output material and energy flows are linked with the respective datasets. The choices of supplying countries and transport distances for inputs are leaned toward import data of the German steel industry (OEC, 2022; Statistisches Bundesamt, 2022; World Steel Association, 2022). Similar to the transport of natural gas in

Germany, the transport of gaseous hydrogen by pipeline is assumed in the future. Additionally, the environmental assessment refers to hydrogen production by polymer electrolyte membrane (PEM) electrolysis with the grid electricity mix in Germany. The electrolysis efficiency is assumed to be 61 %. Thus, the transformation of the energy system highly impacts the upstream GHG emissions of low-carbon steelmaking processes, especially in the case of H/DR. Since breaking down forecasted nationwide hydrogen production capacities to individual steelmakers is not possible, maximum annual hydrogen sourcing quantities are not included.

Future upstream GHG emissions are highly dependent on developments in the background system. In a prospective approach, three potential transformation pathways of the environment are further analyzed to deal with the associated uncertainty. Therefore, Integrated Assessment Model (IAM) scenarios from the REMIND model are included with *Premise*. In this study, scenarios from the Shared Socioeconomic Pathway 2 (SSP2) are used. Based on different climate policies, it is differentiated between three climate trajectories. The scenarios used in this study reflect pathways that lead to expected global warming of around 1.5 °C (*Remind SSP2-PkBudg900*), 2.0 °C (*Remind SSP2-PkBudg1300*), and 3.5 °C (*Remind SSP2-Base*) by 2100. Please refer to the supplementary material for more details on input and output flows, costs of materials and energies, stoichiometric calculations, and Ecoinvent and Premise processes.

### 2.3. Life cycle impact assessment

Projects toward transforming steelmaking are mainly motivated by the associated GHG emissions and the resulting Global Warming Potential (GWP). Therefore, the impact category *IPCC 2013, climate change, GWP 100a* is used for this study's environmental life cycle assessment. The method of system expansion is applied for the assessment of by-products that replace primary raw materials or energies in other industries. Environmental credits for these by-products are included following the avoided burden approach (International Standard ISO 14044, 2006). Externally utilized by-products such as slags are assumed to be fully marketable and to entirely substitute primary materials within other industries, e.g., the cement industry or road construction. Following the recycled content method defined by the World Steel Association, this study does not include an environmental credit or burden due to scrap use (World Steel Association, 2011). This approach is most commonly used in LCA studies on steelmaking. However, the overall impact on climate change highly depends on the methodology used to assess the environmental impacts of material recycling (Suer et al., 2021). Our assessment assumes identical scrap input rates within conventional and low-carbon primary steelmaking processes. Thus, applying other allocation methods, such as the closed material loop method, is expected to only change the impacts of all steelmaking routes to the same extent.

The net present value of cash outflows and the annual real production costs per ton of crude steel are included in the economic assessment of transformation pathways. To this end, market prices and required quantities of materials and energies are considered in each period. Linear depreciation determines the annual capital costs of investments in DR plants and EAFs. Additionally, costs associated with operating and maintaining production facilities are included.

To assess the economic and climate impacts, three different transformation pathways of the foreground system are considered. The costs of materials and energies are assumed not to differ between these foreground system transformation scenarios. Points in time for the substitution of BF-BOF production facilities by DR-EAF production facilities are derived from current strategies of the German steel industry. Usually, steelmakers operate single coking and sinter plants with rich capacities to supply multiple blast furnaces. Since coking and sinter plants are needed for BF-BOF steelmaking, they are assumed to be operated until the end of the transformation period. However, the given capacities are economically favorably utilized each year. All transformation pathways are expected to be completed between 2025 and 2045 to allow compliance with the German climate neutrality target (Press and Information Office of the Federal Government, 2022). Thereby, with the defined transformation steps (Fig. 1c), different transformation speed scenarios' advantages are further investigated. In each transformation step, one-third of the initial capacity for conventional crude steel production is replaced by low-carbon steelmaking facilities.

- *Fast transformation speed*: Transformation over 10 years (step 1 in 2025, step 2 in 2030, and step 3 in 2035).
- *Medium transformation speed*: Transformation over 15 years (step 1 in 2025, step 2 in 2033, and step 3 in 2040).
- *Slow transformation speed*: Transformation over 20 years (step 1 in 2025, step 2 in 2035, and step 3 in 2045).

In all scenarios, either hydrogen or natural gas is used in the DR process. Assuming sufficient DR capacities in all transformation scenarios, no external procurement of hot briquetted iron (HBI) is considered. The economic and environmental impacts of replacing natural gas with hydrogen as a reducing gas for low-carbon steelmaking are compared below.

## 3. Results and discussion

### 3.1. Economic impact assessment of alternative technological routes

The economic impact of transformation scenarios of an illustrative German steel mill is assessed in the section. To calculate the net present value of cash outflows, an interest rate of 5 %/year is assumed, which is in line with previous research (Vogl et al., 2018). Also, an inflation rate of 2 %/year is included, derived from historic inflation rates in Germany (Statistisches Bundesamt, 2020). The net present value of cash outflows is plotted for different reference periods starting in 2022 as the baseline (Fig. 2a-b). It increases by up to 25 % (NG/DR) or 35 % (H/DR) in 2050 if the production infrastructure is transformed toward the DR-EAF route compared to ongoing BF-BOF production. Additional cash outflows for low-carbon steelmaking mainly result from higher prices of materials and energies used in the DR-EAF processes and investments in new production facilities. Regarding transformation speed, a fast replacement of BF-BOF facilities results in a 5 % (NG/DR) to 7 % (H/DR) higher net present value of cash outflows compared to a slow replacement of the BF-BOF route.

The average crude steel production costs increase in each transformation step from BF-BOF toward DR-EAF steelmaking. With 2022 as a baseline for calculating annual crude steel production costs, real costs are used. Thus, future cost increases resulting from inflation are excluded. In the scenario with medium transformation speed, average crude steel costs increase by 11 %/23 %/36 % (NG/DR) or 22 %/36 %/49 % (H/DR) in the first year of operation of new DR-EAF plants in 2025/2033/2040 compared to BF-BOF production. The increase in production costs resulting from a complete transition to NG/DR-EAF or H/DR-EAF steelmaking is in the same range as in previous studies (Jacobasch et al., 2021; Vogl et al., 2018). In the case of H/DR, the difference in crude steel costs between BF-BOF and DR-EAF production significantly decreases toward the end of the transformation process due to an expected decline in hydrogen and electricity costs. Further mitigation of this cost difference is conceivable through various policy measures, such as subsidies for new production facilities or carbon credit costs from emissions trading. Further, additional revenues, e.g., low-carbon steel premiums, can partially offset the higher costs.

Generally, hydrogen and natural gas costs highly influence crude steel costs via the DR-EAF route. Especially at the beginning of the transformation period, using hydrogen leads to significant additional costs compared to natural gas. Average crude steel costs increase by up

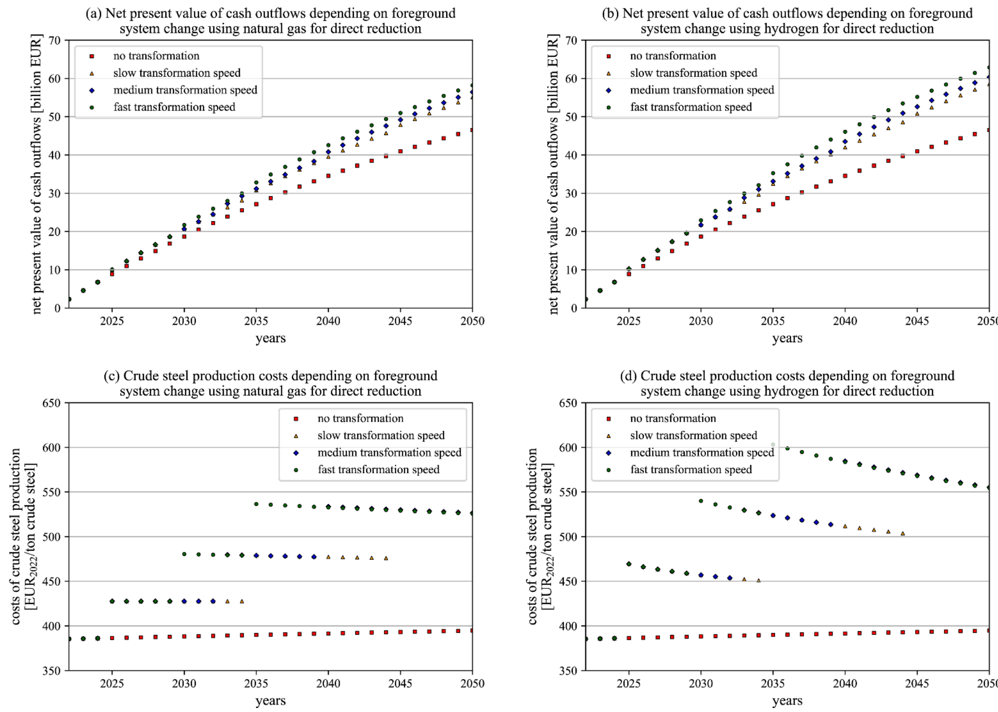


**Fig. 2.** (a) Development of the net present value of cash outflows considering different transformation scenarios toward NG/DR. (b) Development of the net present value of cash outflows considering different transformation scenarios toward H/DR. (c) Development of the real cost for crude steel production considering different transformation scenarios toward NG/DR. (d) Development of the real cost for crude steel production considering different transformation scenarios toward H/DR.

to 10 % if hydrogen is used in the DR plant at the beginning of the transformation process in 2025 compared to using natural gas. Consequently, NG/DR is reasonable from an economic perspective in the first years of the transformation process to minimize additional costs associated with the transformation toward DR-EAF steelmaking. Due to the high uncertainty regarding future hydrogen and natural gas costs, the economic and climate impacts of various cost developments are readdressed with sensitivity analyses in Section 3.3.

### 3.2. Environmental impact assessment of alternative technological routes

In addition to the transformation of the foreground system, three environmental background system transformation scenarios are assessed. We focus on the environmental development of the background system associated with expected global warming of 2.0 °C by 2100. Please refer to the supplementary material for complementary results considering different background system developments.

The overall climate impacts highly depend on the speed of replacing existing facilities from the BF-BOF route with facilities from the DR-EAF route (Fig. 3a-b). The climate impact over the whole time span is expected to decrease by up to 41 % when transforming toward the NG/DR-EAF route compared to no replacement of BF-BOF facilities. If transforming toward H/DR, even higher reductions of up to 53 % are achievable between 2022 and 2050. Thereby, quickly building up DR-EAF capacities results in a 16 % (NG/DR) to 23 % (H/DR) reduction of the overall climate impacts compared to their slow integration. If BF-BOF steelmaking is continued, direct emissions will account for 83 % of all GHG emissions on average. The share of indirect emissions significantly increases as the transformation to DR-EAF steelmaking progresses, indicating the increasing importance of future efforts to mitigate upstream GHG emissions.

Comparing the GHG intensity from NG/DR-EAF (Fig. 3c) and H/DR-EAF steelmaking (Fig. 3d) in the scenario with medium transformation speed indicates that NG/DR is environmentally beneficial to H/DR until 2028 if hydrogen is produced with the projected grid electricity mix in Germany. In this scenario, an emission factor of 0.32 $t_{CO2\text{-}eq}/MWh_{electricity}$ at the beginning and 0.03 $t_{CO2\text{-}eq}/MWh_{electricity}$ at the end of the investigated timespan is assumed. However, this highly depends on the future decarbonization of the energy sector. External market influences can have a significant impact on the development of the electricity mix, as seen in recent years. This can lead to higher emission factors for electricity generation than assumed in our scenarios, especially at the beginning of the transformation period. Thus, investments by steelmakers in renewable energies and electrolyzers could fasten an environmentally advantageous use of hydrogen. With the transformation pathway from BF-BOF to NG/DR-EAF, GHG emissions decrease from around 2.1 $t_{CO2\text{-}eq}/t_{crude\ steel}$ to 0.88 $t_{CO2\text{-}eq}/t_{crude\ steel}$ between 2022 and 2050. Comparable results are reported in previous assessments of BF-BOF and NG/DR-EAF steelmaking processes (Backes et al., 2021; Yilmaz and Turek, 2017). However, future steelmaking still results in 41 % of the current GHG intensity via BF-BOF production. This points out that NG/DR should only be considered an intermediate option in the transformation toward H/DR from an environmental perspective. In this context, the main upsides of natural gas compared to hydrogen are its economic advantages and its higher availability in the near future.

In the case of H/DR, the GHG intensity of crude steel production is 0.42 $t_{CO2\text{-}eq}/t_{crude\ steel}$ in 2050. Compared to BF-BOF production, direct GHG emissions are reduced by 96 % to 0.07 $t_{CO2\text{-}eq}/t_{crude\ steel}$. Previous studies on the emissions mitigation potential of H/DR reported direct emissions of 0.05–0.18 $t_{CO2\text{-}eq}/t_{crude\ steel}$ (Müller et al., 2021; Rechberger et al., 2020; Vogl et al., 2018). However, indirect GHG emissions are projected to remain high until 2050. Several aspects cause this. First, additional GHG emissions for producing and transporting hydrogen and electricity occur. Second, producing and transporting other input materials, such as pellets, pulverized coal, limestone, and graphite, still cause upstream emissions. Third, environmental credits for generating electricity, slag, and other externally used by-products, mainly from BF-BOF production, decrease throughout the transformation process. This indicates the importance of reducing upstream GHG emissions while replacing the steel mill's production infrastructure. Steel manufacturers can directly influence GHG emissions within

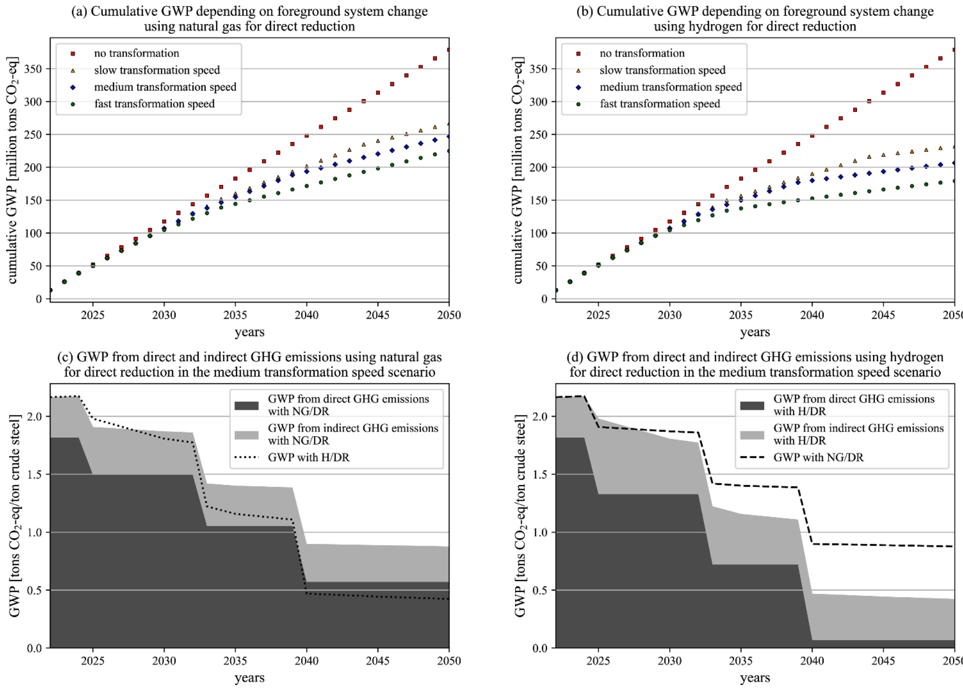


**Fig. 3.** (a) Climate impacts considering different transformation scenarios toward NG/DR. (b) Climate impacts considering different transformation scenarios toward H/DR. (c) Climate impact in the medium transformation speed scenario toward NG/DR. (d) Climate impact in the medium transformation speed scenario toward H/DR.

the raw material supply chain through appropriate incentives. Improving the electricity mix or availability of low-carbon hydrogen needs to be driven by policymakers.

### *3.3. Sensitivity analysis of hydrogen prices, natural gas prices, and transformation speed*

As hydrogen and natural gas are considered substitutes in the direct reduction of iron ore, their costs particularly affect the environmental and economic assessment due to steelmakers' economic behavior. Hence, we conduct sensitivity analyses regarding their cost developments. Therefore, we adapt the cost trajectories for hydrogen and natural gas based on their baseline projections used in previous sections. To this end, the real costs projected for 2050 are varied in steps of 0.5 $EUR_{2022}$/GJ within an interval of +/- 6 $EUR_{2022}$ relative to the baseline. The underlying exponential and logarithmic functions are adjusted accordingly. Overall, we cover 25 cost trajectories for hydrogen and natural gas each.

For these instances, the influence on the net present value of cash outflows and the climate impact is assessed. The net present value of cash outflows differs by 8 % in the range of 54–59 billion EUR (Fig. 4a). Low values occur if either or both hydrogen or natural gas costs have a favorable trajectory. Accordingly, the economically advantageous option is used. However, the substitution highly influences the resulting GHG emissions (Fig. 4b). GHG emissions differ by 16 % depending on hydrogen and natural gas costs and resulting shares for direct reduction. The most significant impact occurs toward the end of the transformation process when the replacement of the production infrastructure is well advanced and low GHG emissions occur from hydrogen production by PEM electrolysis. Thus, the future cost competitiveness of hydrogen compared to natural gas is essential to ensure the environmentally beneficial operation of DR plants. If hydrogen prices continue to stay high, solely NG/DR is used from an economic perspective to minimize crude steel production costs. To enhance H/DR production, hydrogen prices need to decrease significantly faster than in the baseline. Due to the initial cost difference between hydrogen and natural gas, solely NG/DR is applied in all cases in the near future if crude steel production costs are to be minimized. However, short-term increases in the price of natural gas, particularly at the beginning of the transformation process, can significantly impact the cost-effectiveness of the DR-EAF route.

So far, predefined transformation speed scenarios (fast/medium/slow) have been analyzed. However, many more scenarios exist for replacing the steel mills' production facilities over time. When deciding on transformation speed, there is a trade-off between reducing future GHG emissions and costs from steelmaking. To identify eco-efficient pathways, points in time of all three transformation steps are varied between 2025 and 2045. Thus, the fastest transformation is completed all at once in 2025. The slowest scenario assumes the transformation to start and end in 2045. In the case of transforming toward NG/DR, the net present value of cash outflows increases by up to 24 %, and the climate impact decreases by up to 44 % depending on transformation speed (Fig. 4c). Since the H/DR-EAF route allows for even larger GHG emission reductions at higher costs, the net present value of cash outflows and the climate impacts vary by 37 % and 56 %, respectively (Fig. 4d).

Generally, the results indicate that transforming the steel mill over a short period of time is advantageous in terms of eco-efficiency compared to a more extended transformation phase. Transforming over a short period of time leads to reduced costs and emissions compared to longer-lasting scenarios. Hence, besides other effects, fixed operating costs are reduced. In practice, this can only be realized to a limited extent. Continuously high crude steel production volumes must be achieved to keep downstream production areas operating. Also, in integrated steel mills, only a limited amount of space is available to construct new production facilities. Besides these technical aspects, transforming steelmaking entails high investments that steel manufacturers cannot realize all at once. Thus, production facilities must typically be replaced in successive steps, leading to less eco-efficient pathways.

### *3.4. Environmental impact assessment considering increasing primary crude steel production*

In the previous sections, constant annual crude steel production

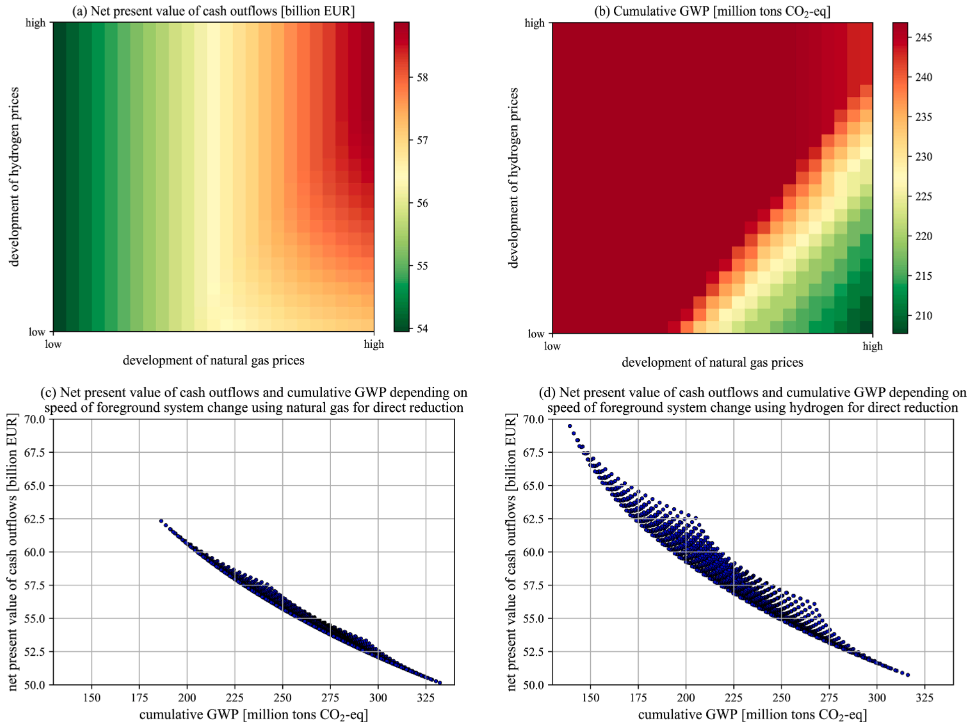


**Fig. 4.** (a) Net present value in the medium transformation speed scenario as a function of hydrogen and natural gas cost developments. (b) Climate impacts in the medium transformation speed scenario as a function of hydrogen and natural gas cost developments. (c) Net present value and climate impacts as a function of transformation speed toward NG/DR. (d) Net present value and climate impacts as a function of transformation speed toward H/DR.

volumes are assumed. However, global primary steel production is expected to further increase in the upcoming decades. As the projected market growth highly influences the overall environmental impact (Hauschild et al., 2020), it is included in the following analyses. To this end, the investigated steel mill's annual crude steel production volume is adjusted based on the projected development of global primary crude steel demands (International Energy Agency, 2020). The functional unit is adapted to the steel mill's predicted annual crude steel production

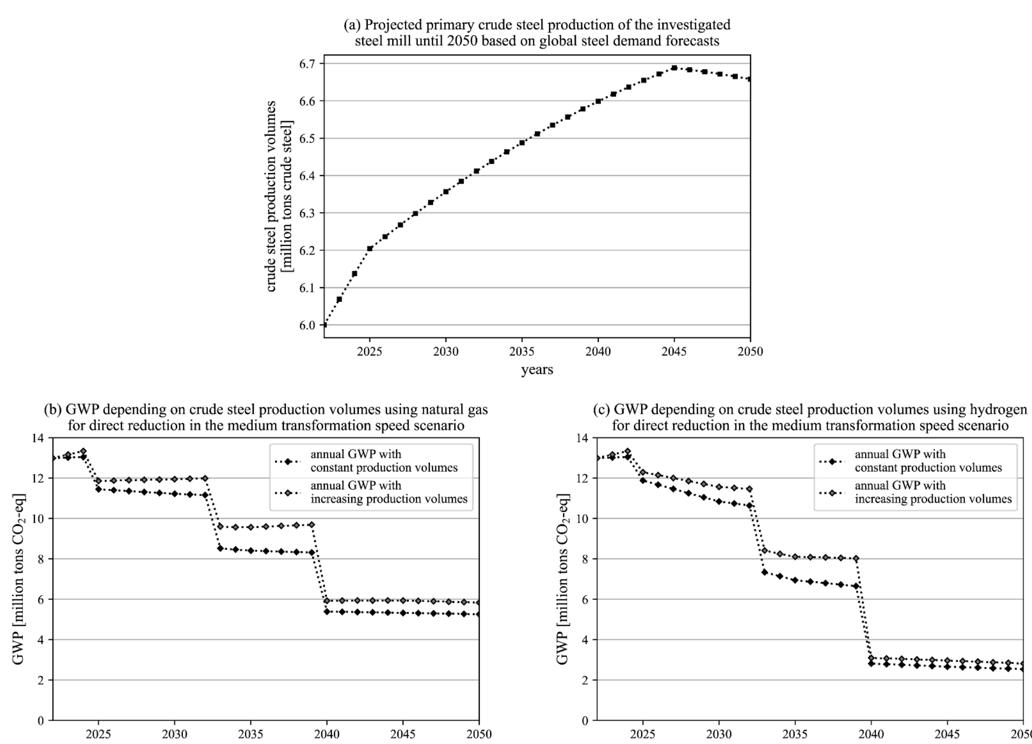


**Fig. 5.** (a) Projected development of primary crude steel production until 2050. (b) Climate impact considering different production volumes in the medium transformation speed scenario toward NG/DR. (c) Climate impact considering different production volumes in the medium transformation speed scenario toward H/DR.

volume (Fig. 5a). To this end, we assume that the BF-BOF route meets additional crude steel demand. Also, the required BF-BOF production capacities are assumed to be available. This is based on the assumption that existing BF-BOF production facilities' lifetimes are extended to fulfill the additional crude steel demands. However, the investigated transformation pathways toward DR-EAF steelmaking do not change.

If BF-BOF production is pursued until 2050, the climate impact increases by around 7 % compared to constant crude steel production volumes. For medium transformation speed toward H/DR or NG/DR, there is an overall increase of 8 % compared to constant crude steel production volumes (Fig. 5b-c). Most additional GHG emissions occur before fully completing the transformation of the steel mill. During this time span, additional crude steel production is met through an extended BF-BOF production. The absolute amount of additional GHG emissions is significantly lower if the production infrastructure is completely transformed toward the DR-EAF route. This again indicates the importance of replacing the production infrastructure as soon as possible from an environmental perspective. Thus, technological improvements allow mitigation of the GHG emission increases caused by higher production volumes.

### 3.5. Implications for steel manufacturers and policymakers

Steel manufacturers motivate the transformation of their processes by reducing GHG emissions by over 90 %. Our results indicate that the achievable reductions are lower if indirect GHG emissions are included. Additionally, a future increase in primary steelmaking quantities might further mitigate the overall GHG emissions reductions. From an economic perspective, crude steel costs will increase stepwise if BF-BOF production is substituted by DR-EAF steelmaking. We can derive the following implications for steel manufacturers and policymakers.

Steel manufacturers should focus on *supply chain decarbonization* to ensure a reduction of upstream GHG emissions and report accordingly. To this end, incentives need to be established for suppliers to reduce the emissions associated with the mining and transport of raw materials. *NG/DR is an environmentally and economically viable intermediate solution* at the beginning of the transformation process if hydrogen is not produced from renewable energies. However, to heavily reduce the climate impact of steelmaking, *shifting toward hydrogen in the DR process* is required in the future. Therefore, GHG emissions from the *generation of electricity and hydrogen* need to be minimized. Electrolysis capacities combined with renewable energy sources can be integrated into steelmaking plants. Also, participation in off-site energy projects to obtain low-carbon electricity and hydrogen at an early stage may be considered.

Shifting to low-carbon steelmaking processes results in a significant increase in electricity demand. In contrast to the relatively small electricity demand of BF-BOF processes of 0.14 $MWh/t_{crude\ steel}$, NG/DR-EAF requires 0.55 $MWh/t_{crude\ steel}$ and H/DR-EAF requires 3.91 $MWh/t_{crude\ steel}$ if the electricity demand for hydrogen production is included. Also, no by-product gases are produced in the DR-EAF processes, which are used for electricity generation in the case of BF-BOF steelmaking. Policymakers must acknowledge that the *energy sector will become even more important* regarding indirect GHG emissions in the future. Thus, fast decarbonization of the energy sector is required. Transitioning to a low-carbon electricity system seems possible in the coming decades. However, the next few years will be the most challenging due to the retirement of large fossil fuel capacities besides the high investment need to expand renewable energy sources (Bogdanov et al., 2019). In addition to decarbonizing the electricity system, expanding the infrastructure for hydrogen production and transport is required. This is even more important considering the complicated political situation concerning natural gas supply in Europe.

Economically, *markets or premiums for low-carbon steel* must be supported by appropriate measures to compensate for additional expenditures and higher production costs. Also, *subsidies for new production facilities* for low-carbon steelmaking lead to smaller cost increases for crude steel throughout the transformation toward DR-EAF steelmaking. Recently, European legislation paved the way for governmental subsidies to accelerate the steel industry's decarbonization (Salzgitter, 2022b).

## 4. Conclusion

The article at hand assesses the environmental and economic impacts of different transformation scenarios that aim to reduce GHG emissions from primary steelmaking, including BF-BOF, H/DR-EAF, and NG/DR-EAF routes. Therefore, projections on future developments of the environment are included based on prospective life cycle assessment. The developed assessment provides an understanding of the impacts of various transformation pathways for integrated steel mills, considering the interdependencies of material and energy flows between the routes. Besides the assessment of constant crude steel production throughout the transformation, the climate impact of increasing production volumes is analyzed.

The results indicate that a faster transformation of steel mills leads to an increased net present value of cash outflows. Crude steel costs increase significantly throughout the transformation. This suggests that steel manufacturers require assistance in their transformation to achieve a fast reduction of GHG emissions in an economically sound way. Potential measures are surcharges for green steel or governmental subsidies for investments. NG/DR will provide a suitable intermediate technology environmentally and economically in the upcoming years. However, H/DR needs to be expanded quickly to minimize long-term GHG emissions. Generally, transforming and decarbonizing the upstream value chain of steelmaking is highly important. Indirect GHG emissions will become even more critical during the transformation toward DR-EAF production.

In our study, we investigated potential transformation scenarios of primary steelmaking from BF-BOF toward DR-EAF processes in Germany. Economic and climate impacts in other regions may differ from the reported findings. Also, forecasts on developments within the system environment are based on IAM scenarios. These developments are significantly influenced by political decisions and technological advances. Future research might extend the developed approach with other technological options for decarbonizing steelmaking. In this context, both short- and long-term measures for reducing GHG emissions are of interest. Interdependencies with secondary steelmaking might be included, considering increasing scrap returns over time. Also, DR-EAF allows for higher scrap metal input rates in primary steelmaking compared to conventional BF-BOF processes, leading to further emission reduction potentials. This study analyzes the economic and climate impacts of predefined transformation pathways. An assessment of legislative measures such as subsidies or carbon credit costs from emissions trading systems still needs to be included. To identify optimal transformation pathways considering potential legislative measures, a model-based design of advantageous transformation pathways might be promising to support steelmakers' decision-making. Also, other environmental indicators might be included in the assessment to allow for a broader evaluation of transformation scenarios toward low-carbon steelmaking technologies.

## CRediT authorship contribution statement

**Christian Weckenborg:** Conceptualization, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Yannik Graupner:** Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Thomas S. Spengler:** Resources, Supervision, Writing – review & editing.

## Declaration of competing interest

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.

## Data availability

Supplementary material associated with this article can be found in the online version.

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## Supplementary materials

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