Green Steel – Life cycle modeling of an integrated steel site

Carbon footprint and energy transformation analysis of decarbonized steel production

Von der Fakultät für Bauingenieurwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften genehmigte Dissertation

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Abstract

The steel industry is focused on reducing its environmental impact. Steel is typically produced primarily from iron ores in integrated sites and secondarily from scrap recycling in electric arc furnaces (EAF). Traditional integrated sites include hot metal generation via the blast furnace route, basic oxygen steelmaking (BOF), continuous casting, and subsequent hot-rolling. For the evaluation of environmental impacts generated by the product, the life cycle assessment (LCA) methodology according to ISO 14040/44 has been used. The LCA is internationally recognized and standardized. Using the LCA methodology, the impacts of primary steel production via the blast furnace route and the secondary scrap-based steel production via the EAF route are assessed. These production routes represent the state-of-the art. Subsequently, decarbonization strategies are analysed using the product carbon footprint (PCF) methodology according to ISO 14067.

In a blast furnace coal and coke are used for the reduction and melting of iron ores. The decarbonization of the steel industry requires a shift from a coal-based metallurgy towards a hydrogen and electricity-based steel production, or purely electric, if the utilized hydrogen stems from electrolysis. The blast furnace can be substituted by direct reduction (DR) plants with subsequent electrical melting. In DR plants, iron oxides can be reduced by natural gas as well as pure hydrogen. DR plants have reached capacities, which allow replacing blast furnaces on a direct basis. While the majority of European steel producers have pointed to direct reduced iron (DRI) production as a key part of their decarbonization targets, the next steps are highly discussed. Two main routes stand out: (1) Melting and processing the DRI in an EAF directly to crude steel; (2) Melting and carburizing the DRI in an electric melting unit to hot metal. The hot metal is then further refined in a BOF to crude steel. Whereas the first route seems to be more straightforward, some metallurgical points require discussion.

On the basis of the carbon footprint methodology different scenarios of a stepwise transition are evaluated and values of possible CO_2equivalent (CO_2eq) reduction are coupled with the demand of hydrogen, electricity, natural gas, and coal. For example, while the traditional blast furnace - BOF route delivers a surplus of electricity in the range of 0.7 MJ/kg hot-rolled coil; this surplus turns into a deficit of about 17 MJ/kg hot-rolled coil for a hydrogen-based steel production route. On the other hand, while the product carbon footprint of the blast furnace-related production route is 2.1 kg CO_2eq/kg hot-rolled coil; this footprint can be reduced to 0.75 kg CO_2eq/kg hot-rolled coil for the hydrogen-related route, obtained with electricity input generated by renewable sources. Thereby the direct impact of the processes of the integrated site can even be reduced to 0.15 kg CO_2eq/kg hot-rolled coil. The remaining carbon footprint is caused by upstream processes for which no improvements are considered. However, if the electricity input has a carbon footprint related to the German or European electricity grid mix, the respective carbon footprint of hot-rolled coil increases up to 3.0 kg CO_2eq/kg hot-rolled coil. A natural gas-based DR production route leads to a carbon footprint of 1.4 - 1.7 kg CO_2eq/kg hot-rolled coil, depending on the electricity mix used for the steel production processes. A detailed break-even analysis is given, comparing the use of natural gas and hydrogen using different electricity mixes.

Intermediate scenarios can enable a stepwise transition of changed plant configurations and material and energy related feedstocks. Simultaneously, the intermediate scenarios lead to PCF reductions in time. In this dissertation the scenarios hydrogen and natural gas injection into a blast furnace and the use of hot briquetted iron (HBI) in a blast furnace are analyzed.

Keywords: Life cycle assessment; Carbon footprint assessment; Steel; Direct reduction; electric melting

Zusammenfassung

Die Stahlindustrie steht im Fokus, umweltfreundlicher zu produzieren. Stahl wird typischerweise primär aus Eisenerzen in integrierten Hüttenwerken und sekundär durch Recycling von Stahlschrott in elektrischen Lichtbogenöfen produziert. Klassische integrierte Hüttenwerke bestehen aus der Roheisenproduktion über die Hochofenroute, der Rohstahlherstellung in Konvertern, der Sekundärmetallurgie, dem Stranggießen sowie dem Warmwalzen.

Für die Bewertung von Umwelteinwirkungen eignet sich die international etablierte Lebenszyklusanalyse (engl.: Life Cycle Assessment – LCA) nach ISO 14040/44. Mithilfe der LCA-Methodik werden die Umwelteinwirkungen der primären Stahlproduktion über die Hochofenroute sowie der sekundären Stahlproduktion über das Stahlschrottrecycling in Lichtbogenöfen bewertet. Diese Produktionsrouten repräsentieren den Stand der Technik. Darauf aufbauend werden Strategien zur Dekarbonisierung analysiert mithilfe der - Product Carbon Footprint (PCF) - Methodik nach ISO 14067.

In Hochöfen werden Eisenerze mithilfe von Kohle und Koks reduziert und eingeschmolzen. Die Dekarbonisierung der Stahlindustrie erfordert einen Wechsel von kohlebasierter Metallurgie zu wasserstoff- und strombasierter Stahlerzeugung, bzw. rein strombasiert, wenn der Wasserstoff aus Elektrolyse stammt. Der Hochofen kann substituiert werden durch eine Direktreduktionsanlage (DR-Anlage) mit nachgeschalteten elektrischen Einschmelzaggregaten. In DR-Anlagen können Eisenoxide mit Erdgas oder auch reinem Wasserstoff reduziert werden. Die Anlagen haben bereits den Hochöfen ähnliche Produktionskapazitäten erreicht. Während die Mehrheit der europäischen Stahlproduzenten DR-Anlagen bereits als Schlüsseltechnologie identifiziert hat, werden die darauffolgenden Prozessschritte intensiver diskutiert. Zwei Routen stechen hierbei heraus: (1) Das direkt reduzierte Eisen (DRI) wird in einem elektrischen Lichtbogenofen (engl.: electric arc furnace - EAF) eingeschmolzen und direkt zu Rohstahl gegossen; (2) Das DRI wird in einem elektrischen Einschmelzer eingeschmolzen und zu Roheisen aufgekohlt. Das Roheisen wird anschließend wie gewohnt in Konvertern zu Rohstahl verarbeitet. Auch wenn die erste Route zielgerichteter erscheint, so müssen einige metallurgische Aspekte diskutiert werden.

Basierend auf der PCF-Methodik werden verschiedene Szenarien einer schrittweisen Transformation bewertet und Einsparungen an CO_2equivalenten werden gekoppelt an Verbräuche von Wasserstoff, Strom, Erdgas und Kohle. Während die klassische Hochofenroute bspw. einen Stromüberschuss von etwa 0,7 MJ/kg Warmband generiert, so dreht sich dieser Überschuss in ein Defizit von etwa 17 MJ/kg für eine wasserstoffbasierte Stahlproduktion. Auf der anderen Seite, während der Stahl, produziert über die Hochofenroute, einen PCF von etwa 2,1 kg CO_2eq/kg Warmband aufweist, so kann dieser PCF

reduziert werden zu 0,75 kg CO_2eq/kg für die wasserstoffbasierte Route, vorausgesetzt der Strom sowie der Wasserstoff stammen aus erneuerbaren Energien. Dabei kann der Einfluss der Prozesse eines integrierten Hüttenwerkes sogar bis auf 0,15 kg CO_2eq/kg Warmband reduziert werden. Der verbliebene CO_2-Fußabdruck wird durch die vorgelagerten Prozesse verursacht, für die keine Verbesserungen angenommen sind. Wenn der Strominput jedoch nicht erneuerbar ist, sondern bspw. aus dem derzeitigen deutschen Strommix stammt, so erhöht sich der PCF auf 3,0 kg CO_2eq/kg Warmband für die H_2-basierte Produktionsroute. Die erdgasbasierte DR-Route führt zu einem PCF zwischen 1,4 und 1,7 kg CO_2eq/kg Warmband in Abhängigkeit des verwendeten Strommixes. Eine detaillierte Break-even Analyse wird in dieser Dissertation durchgeführt, in der der Einsatz von Erdgas mit Wasserstoff aus verschiedenen Strommixen verglichen wird.

Übergangsszenarien zur klimaneutralen Stahlproduktion können dabei unterstützen, die Anlagenkonfigurationen sowie die damit verbundenen Material- und Energieinputs schrittweise anzupassen. Dabei bieten sie gleichzeitig die Chance erste PCF-Einsparungen zu erzielen. In dieser Dissertation werden die Szenarien Einblasen von Wasserstoff und Erdgas sowie der Einsatz von vorreduziertem Eisen im Hochofen analysiert.

List of publications

Suer, J.; Traverso, M.; Jäger, N.: Review of Life Cycle Assessments for Steel and Environmental Analysis of Future Steel Production Scenarios. Sustainability, 14(21), 14131 (2022). https://doi.org/10.3390/su142114131

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Suer, J.; Traverso, M.; Jäger, N.: Carbon Footprint Assessment of Hydrogen and Steel. Energies 2022, 15(24), 9468. https://doi.org/10.3390/en15249468

Suer, J.; Traverso, M., & Ahrenhold, F. (2022). Sustainable transition of the primary steel production: Carbon footprint studies of hot-rolled coil according to ISO 14067. In E3S Web of Conferences (Vol. 349, p. 07004). EDP Sciences

Suer, J.; Ahrenhold, F. Integration of DRI plants into classical BOF production sites. In Proceedings of the 5th ESTAD, Stockholm, Sweden, 30 August–2 September 2021

Backes, J. G.; Suer, J.; Pauliks, N.; Neugebauer, S.; Traverso, M. (2021). Life cycle assessment of an integrated steel mill using primary manufacturing data: actual environmental profile. Sustainability, 13(6), 3443

Kolbe, N.; Cesário, F.; Ahrenhold, F.; Suer, J.; Oles, M. (2022). Carbon Utilization Combined with Carbon Direct Avoidance for Climate Neutrality in Steel Manufacturing. Chemie Ingenieur Technik, 94(10), 1548-1552

List of abbreviations

CCfD	Carbon contract for differences
CCS	Carbon capture and storage
CCU	Carbon capture and usage
CCUS	Carbon capture use and/or storage
CDA	Carbon direct avoidance
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
COG	Coke oven gas
BF	Blast furnace
BFG	Blast furnace gas
BOF	Basic oxygen furnace
BOFG	Basic oxygen furnace gas
DR	Direct reduction
DRI	Direct reduced iron
EAF	Electric arc furnace
EU	European Union
FeO	Iron oxide (wustite)
GHG	Greenhouse gas
GWP	Global warming potential
H_2	Hydrogen
HBI	Hot-briquetted iron
HRC	Hot-rolled coil
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
N_2O	Nitrous oxide (laughing gas)
NG	Natural gas
PCF	Product carbon footprint
tkse	thyssenkrupp Steel Europe AG
TRL	Technological readiness level

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1 Introduction

The goal of a climate neutral steel is an important challenge faced by humanity. In order to prevent irreversible damage, global warming has to be kept well below 2°C, preferably below 1.5°C [1]. Within the European Green Deal for the European Union (EU) and its citizens, the EU has set the target to become climate neutral by 2050 and to reduce greenhouse gas (GHG) emissions by at least 55% by 2030, compared to 1990 levels [2]. The energy-intensive steel industry is responsible for roughly 7% of global anthropogenic carbon dioxide (CO_2) emissions [3]. Thus, the decarbonization of the steel industry presents a major challenge, but at the same time a tremendous opportunity. Steel is firmly established in society and makes an important contribution to achieve the climate goals. Steel is an important bulk material, which serves as key input to the building, electrification, infrastructure, transport, machinery, and consumer goods sectors [3,4]. In the year 2021, about 1.95 Gt of steel were produced, globally [5]. Future steel demand is expected to be approximately 2.5 Gt per year by 2050 [3]. The increasing steel demand is the reason, why in spite of efficiency gains, the absolute steel related GHG emissions are still increasing [6].

Steel is produced primarily with natural iron ores and secondarily with recycled scrap. In 2021, the share of the primary blast furnace route was 70.8% and the share of the secondary scrap recycling route via an electric arc furnace (EAF) was 28.9% [5]. However, since scrap is used as a cooling material in the primary blast furnace route the total amount of steel produced out of recycled scrap amounts to 32% globally. The share of scrap for steel production is expected to rise to 46% in 2050 [7]. Thus, primary steel production will remain a necessity to meet demand growth. Within the primary production route, reduction of iron ores is required, and the gangue needs to be separated from the iron ores. This is not required in the scrap-based recycling route. Therefore, the blast furnace - basic oxygen furnace (BF-BOF) route's average primary energy demand is about 23 GJ/t steel, whereas the scrap-based EAF route's average primary energy demand is about 5.2 GJ/t steel [3]. In the same way the direct and indirect CO_2 emissions are 2.2 t CO_2/steel for the primary BF-BOF route and 0.3 t CO_2/t steel for the secondary scrap based EAF route [3].

In order to reach the climate goals a decarbonization of the steel industry is mandatory. Several production pathways are in discussion to manage the shift from a coal-based metallurgy, preferably towards an electricity- and hydrogen-based steel production (carbon direct avoidance – CDA). The continuation of a fossil-based steel production in combination with carbon capture, use, and/or storage (CCUS) is also a discussed pathway [3,7,8,9]. CCUS can also be used as supplement to a CDA strategy. In combination with the use of biomass CCUS could yield a negative CO_2 balance [8,10].

The majority of European steelmakers commit to steel production via direct reduction (DR) plants in combination with electrical melting as the key part of their decarbonization strategies [7,10,11]. This technology allows a shift from a coal-based metallurgy towards a hydrogen and electricity-based steel production. Other CDA related technologies such as iron ore electrolysis suffer from a low technology readiness level (TRL) for a large-scale production [8,10]. In this dissertation steel production via a DR plant in combination with electrical melting is discussed from a technical and environmental perspective. Modified blast furnace operations as intermediate scenarios towards climate neutral steel production are also topic of this dissertation. The use of new energy or material sources such as hydrogen in existing blast furnaces can accelerate the buildup of a hydrogen infrastructure.

The environmental impacts of steel production are assessed in this dissertation using the life cycle assessment (LCA) methodology according to ISO 14040 [12] and ISO 14044 [13] as well as the product carbon footprint (PCF) methodology according to ISO 14067 [14]. An LCA includes the entire product life cycle from raw material extraction to supply, product manufacturing, use, recycling, and the disposal of waste, otherwise known as cradle-to-grave approach.

This chapter summarizes a technical state-of-the art of steel production (section 1.1) and describes the technical transformation path (section 1.2). The state-of-the art of LCAs on steel production is presented (section 1.3). Research questions, and how these correspond to the presented publications are explained in section 1.4, and the structure of the dissertation is shown in section 1.5.

1.1 State-of-the art of steel production

Steel is produced mainly via two dominant routes, the primary BF-BOF route and the secondary steel scrap recycling route via an EAF [5]. In section 1.1.1 the BF-BOF route is explained, in section 1.1.2 the scrap-based EAF route is discussed.

1.1.1 Primary blast furnace related steel production

Primary steelmaking is a domain of integrated steel sites. An integrated steel site typically consists of a sinter plant, coke plant, BF, BOF, secondary metallurgy, and continuous casting, see figure 1. The goal of an integrated steel site is the processing of iron ores into steel. Therefore, iron oxides need to be reduced and the gangue needs to be separated from the iron. Both process steps are done in a BF by coal and coke. Iron oxides, fluxes and coke are inserted from the top of the shaft furnace. Pulverized coal is injected in the lower part of the furnace by tuyeres. The coal and coke are oxidized by injected hot blast and oxygen to carbon dioxide (CO_2). At high temperatures and the presence of carbon, CO_2 reacts to carbon monoxide (CO) according to the Boudouard reaction. The CO arises and reduces the counterflowing iron oxides. At the top of the furnace the gas leaves the BF as BF gas (BFG), consisting of N_2, CO, CO_2, and H_2. Before the hot blast is injected into the BF it is preheated in the hot blast stoves. The hot blast stoves are an auxiliary unit of the BF and are included in the process of the BF, see figure 1. The product of the BF process is liquid hot metal, which contains about 4.5% carbon. The gangue of the iron oxide is converted into an oxidized slag, which swims on top of the hot metal due to its lower density. The slag is quenched with water to create latent hydraulic properties. The granulated slag serves as portland cement clinker substitute. [15]

In figure 1, there are two processes, delivering inputs for the BF: a sinter plant and a coke plant. The iron oxides used in a BF must not be too fine since a good gas permeability is necessary in the shaft furnace. Thus, the iron ores are generally brought in as lump ore, graded sinter, or iron ore pellets. When iron ore is extracted from the mine, it is crushed and screened. Roughly speaking, it can be distinguished between lump and fine streams. The iron content is typically concentrated, e.g. by spirals, floatation, or magnetic separation [15,16]. The fines are pelletized or sintered for making them usable for a BF operation. The process of pelletization consists of formation green balls by rolling of moist iron ore fines with binders. The green pellets are further hardened at temperatures between 1200-1300°C [17]. In a sinter plant, fine iron ores, fluxes, and residues from an integrated site are baked in a sinter bed. Coke breeze, which is added to the mix, serves as energy supplier. In figure 1 the sinter plant is inside the processes of the integrated size since sinter plants are typically located next to blast furnaces, whereas pellet plants are located near the iron ore extraction [16].

In the coke plant coal is pyrolyzed to coke. In a group of ovens – the coke oven battery – coal is heated to a temperature about 1100°C in the absence of oxygen. The volatile components are removed from the coal, generating a hydrogen-rich coke oven gas (COG). The product, coke, is a solid and permeable material up to very high temperatures (> 2000°C), which makes it suitable for the BF process [17].

Finally, the lump ore, the pellets, and the sinter are reduced and melted in a BF by coal and coke to hot metal as described previously. The hot metal is further refined in a BOF to crude steel. Oxygen is blown into the BOF, and binds to the carbon of the hot metal, leaving the process as CO-rich offgas, the BOF gas (BOFG). Due to the highly exothermic oxidation reactions, scrap is brought in as cooling material. An oxidized slag remains as co-product. The slag is crushed and grinded. Using magnetic separation, iron-rich components are partially recovered and reused e.g., directly in the converter process or alternatively in the blast furnace or sintering process. The remaining slag is mainly used as material for road construction and as fertilizer. The crude steel is further processed to high-quality steel in the so-called secondary metallurgy. Here e.g., alloying elements are added, the steel is further homogenized, or the steel is vacuum treated. After undergoing secondary metallurgy crude steel is defined as steel. The liquid steel is cast into a strand over a continuous casting line and cut into slabs, ingots, blooms, or billets.

Besides the described aggregates used for steelmaking, an integrated steel site typically includes a power plant, see figure 1. The process gases from the coke plant, the BF, and the BOF are primarily used for heat supply for the integrated processes. Excess process gases are thermally used in a power plant to produce electricity and steam.

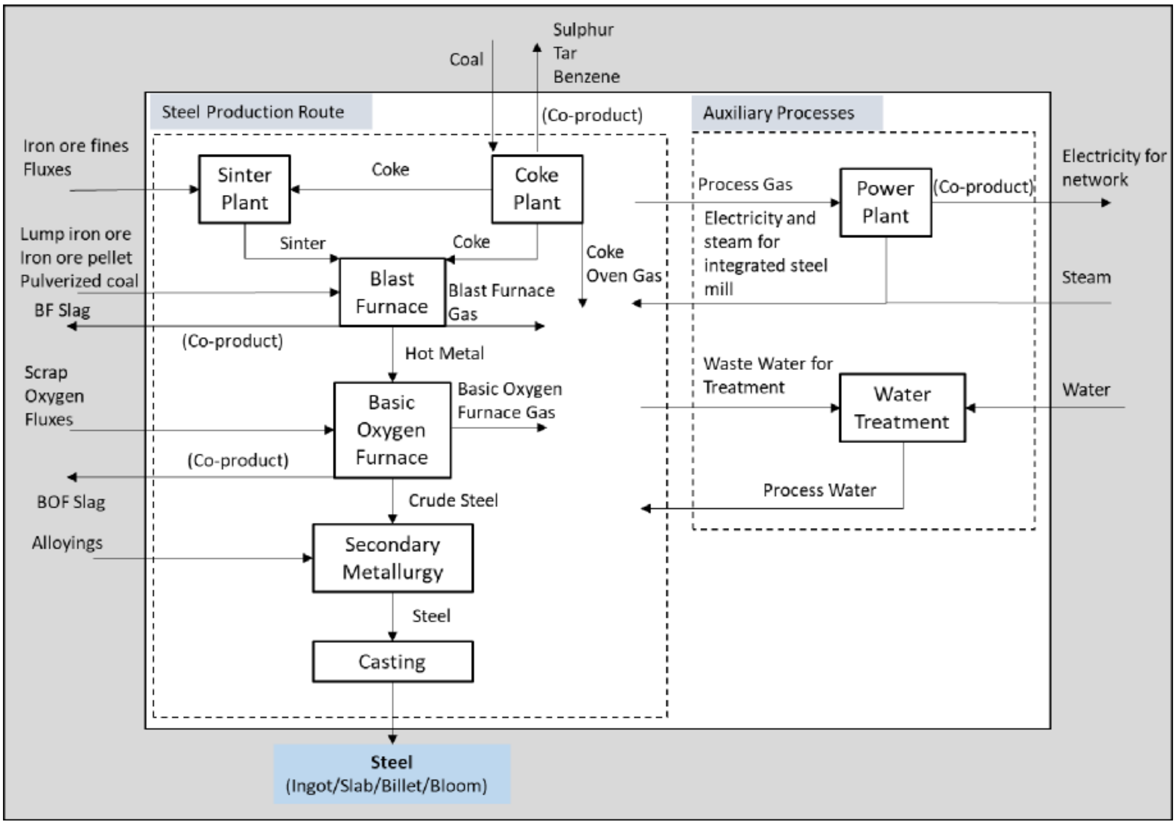

Figure 1: Steel production via an integrated steel site.

1.1.2 Secondary steel recycling route via an electric arc furnace (EAF)

The recycling of scrap to steel is typically done in an EAF. The addition of virgin materials like hot metal, DRI, or hot briquetted iron (HBI) to the scrap charge is also an option. The melting of steel is achieved using electrical and chemical energy. The electrical energy is added to the scrap charge by multiple electrodes generating an electric arc. The electric arc reaches temperatures of up to 3500°C. The injection of oxy-fuel or oxygen can introduce additional energy and accelerate the melting period [16]. Furthermore, carbon is charged into the process, mainly in form of coal or coke. The oxidation of iron (Fe), silicon (Si), carbon (C), and other elements releases a large amount of heat, which reduces the melting time [17].

During the refining period elements like phosphorous, silicon, and manganese are oxidized and transformed into slag. Iron is oxidized and transferred into the slag as well, which reduces the iron yield [17]. Fluxes like lime are added to adjust the slag properties, which also controls the steel's quality. Carbon and oxygen form gaseous CO, which has several advantages: The bubbling of the CO gas through the molten metal effects (i) a positive slag-metal contact, (ii) good heat transfer, (iii) homogenization of the bath, and (iv) dissolved nitrogen and hydrogen gases diffuse into the CO bubbles and are flushed out the molten bath [17]. In addition, the CO bubbles also foam the slag. The foamed slag envelopes the electrodes, which reduces radiation losses and protects the refractories [18].

Within the secondary metallurgy the crude steel is further processed to steel. Important tasks are e.g., the desulphurisation by fluxes like lime or calcium carbide, the deoxidation of the metal, or the charging of alloying elements [16,19]. The liquid steel is cast over a continuous casting line into a strand and cut into slabs, ingots, blooms, or billets.

The CO-rich process gas from the EAF can be incinerated and thus used for thermal heat supply e.g., for preheating of scrap, which results in lower energy requirements of the EAF process [17]. The resulting slag can be used for construction such as roadworks [20].

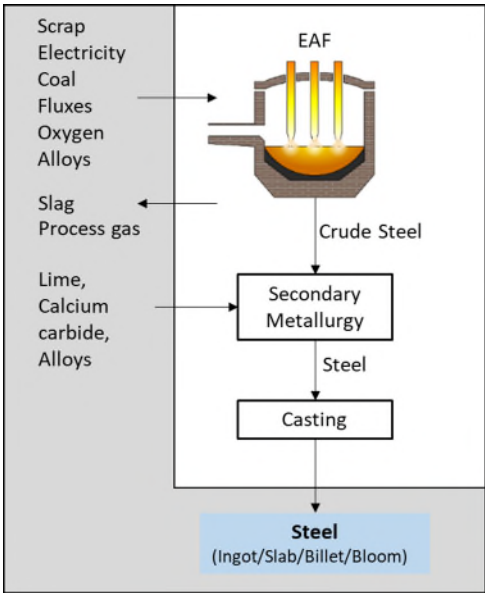

Figure 2: Steel production via the scrap-based recycling route with an electric arc furnace (EAF)

A challenge of scrap recycling is the fact that scrap contains impurities, such as copper, cobalt, tin, chrome, phosphorous, zinc etc. While some are transferred into the slag during the refining period or into the process gas, others are ultimately concentrated in the produced steel. This limits the quality of steel products from scrap recycling and also complicates the slag and process gas handling [17]. However, the closed loop of recycling scrap to steel, the comparably low energy requirements, and the flexible operation mode are some important advantages of the scrap-based recycling route [17].

1.2 Technical transformation of the steel industry

The majority of European steelmakers have pointed to direct reduced iron (DRI) production as a key part of their decarbonization targets [10,11]. Direct reduction (DR) modules have reached capacities of above 2.5 million tonnes and can compete with blast furnaces with the limitation that iron oxides are only reduced in a DR plant but not melted [21,22]. Thus, the direct reduced iron (DRI) still contains gangue. In a shaft furnace operation, various gases are used as sources of the reducing gases hydrogen (H_2) and carbon monoxide (CO): natural gas, hydrogen, coke oven gas (COG), basic oxygen furnace gas (BOFG), etc. Operation exclusively with hydrogen is also possible [23]. In a subsequent process the gangue can be removed, preferably by using electrical energy, and further processed to steel. The potential to use hydrogen as a reducing agent in a DR plant in combination with electric melting has the potential to decarbonize the steel production.

Whereas DRI production seems to be like consensus, the further steps are highly discussed [10,11]. Two main routes stand out for further processing:

1. The DRI is melted in an EAF, and the melt can be directly cast into crude steel.
2. The DRI is melted and carburized in an electric melting unit (e.g., an open slag bath furnace) to hot metal. The hot metal is further refined in a BOF to crude steel. [10,11]

The first route seems to be more straightforward since it also replaces BOFs. However, some metallurgical points need to be further investigated, and they are part of this dissertation.

Ultimately, steel production can be shifted from a coal-based BF-BOF route towards H_2-DRI with electrical melting. Thus, the reduction of iron ores is shifted from coal to hydrogen and the melting is shifted from coal to electricity based. The hydrogen can be produced electrically by electrolysis. If the electricity, for both the hydrogen electrolysis and the electric melting, is from renewable sources, steel production can be nearly completely decarbonized. Some metallurgical carbon is still required for the melting process, in both routes (1) and (2), which also needs further discussion. From an environmental perspective, the production of electricity and hydrogen are the main focus.

Steel manufacture plants are very complex systems with highly integrated material and energy flows. Besides the configurations of the system also the material and energy related feedstocks need to be transformed. E.g., coal imports are substituted for hydrogen and electricity imports. Therefore, sufficient hydrogen and renewable electricity are required, and an infrastructure has to be established. Intermediate scenarios can enable a stepwise transition of changed plant configurations and material and energy related feedstocks. Simultaneously, the intermediate scenarios lead to gradual GHG reductions over time. In this dissertation four BF related intermediate scenarios are investigated:

- Injection of hydrogen into a BF
- Injection of natural gas into a BF
- Use of natural gas-based HBI in a BF
- Use of H_2-based HBI in a BF

1.3 Life cycle assessment of steel

Life cycle assessment is an international standardized methodology according to the norms ISO 14040 and ISO 14044 [12,13]. If the focus of the assessment lies on the sole impact category of climate change, it is referred to the methodology product carbon footprint (PCF) assessment according to ISO 14067 [14].

An LCA and PCF consist of four phases

(1) Goal and scope definition

(2) Life cycle inventory (LCI) analysis

(3) Life cycle impact assessment (LCIA)

(4) Interpretation

Within phase (1) the goal as well as the scope of the study are defined. For the definition of the scope the following points are described: the functions of the product system, the functional unit, the system boundary, the allocation methods, the methodology for the LCIA, the methodology for the evaluation, the data requirements, the assumptions and limitations of the study, and the type of critical review, if considered [13]. The functional unit describes the function of the product according to the defined goal of the study. In general, the system boundary should consider the whole product life cycle, i.e., from cradle-to-grave. However, a restricted system boundary such as cradle-to-gate or even gate-to-gate is also possible [12]. E.g., in the case of the product steel a cradle-to-grave system boundary is generally not practical since steel has numerous applications. A possible solution to this issue is the exclusion of the use phase and to conduct a cradle-to-gate assessment. Thus, all environmental impacts are assessed from the raw material supply to the product, which leaves the plant gate, e.g., steel. In this case a functional unit cannot be distinguished since the applications of steel are many. As such a declared unit of steel is defined instead.

Allocation is necessary when co-products are produced or used in a product system. The inputs and outputs are allocated to the different products. The allocation is usually referenced to mass, energy, or price of the products [13]. However, the ISO 14044 recommends the avoidance of allocation since the choice of allocation method can strongly influence the results. The methodology of system expansion avoids allocation. A production system is added, which is assumed to be replaced by the co-product and credits are given for the substituted environmental impacts [13].

Within phase (2) – LCI analysis – all input and output data are collected for the process system. The data can be categorized into:

- energy as well as material related inputs and other physical inputs
- products, co-products, and waste
- emissions in air, water, and soil
- further environmental aspects [13]

The collected data need to be validated by e.g., mass and energy balances or the inputs and emissions can be linked via emission factors.

Within phase (3) – LCIA – two mandatory phases are defined by the ISO 14040/44; the classification and characterization phases. The classification consists of to classify and assign all emissions of the LCI to the chosen impact categories. The characterization phase allows characterizing (translating) the emission in impacts throughout a characterization factor. In case of the impact category climate change the global warming potential (GWP) is the indicator used: each greenhouse gas characterizes its impact on climate change in comparison to CO_2, see figure 3. The characterization factor depends on the time frame, which is considered. E.g., methane exists in the atmosphere for about 12 years. As a result, the GWP of methane is 30 kg CO_2eq/kg for a considered time span of 100 years (GWP 100), but 83 kg CO_2eq/kg for a time span of 20 years (GWP 20) [24].

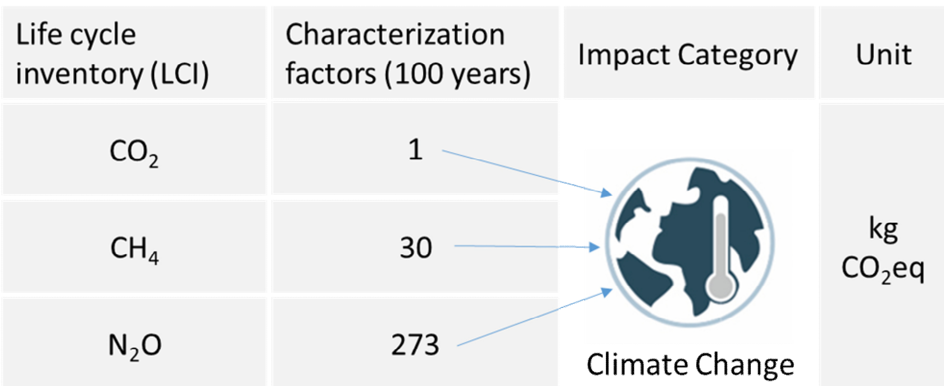

Figure 3: From emissions to an environmental impact category at the example of climate change. Characterization factors from [24].

Other life cycle impact categories are: acidification, eutrophication, ozone depletion etc. [25]. These are defined as midpoint categories, expressed by the midpoint indicator. In case of the impact category climate change the midpoint indicator is the GWP. The midpoint indicator is a measurable quantity, which can be calculated from the emissions.

The consequences of the midpoint categories are defined as endpoint categories [26]:

- damage to human health
- damage to ecosystem diversity
- resource scarcity

Endpoint categories describe the damage, which results from the impact categories to specific areas of protection. Thus, they are crucial for political decision makers. E.g., the IPCC describes the damage, which results from an increased climate change e.g., weather extrema [24]. In this dissertation the focus is on midpoint categories.

In phase (4) – interpretation – the results of the LCI and of the LCIA are analyzed. Significant parameters like emissions, wastes, or impact categories are identified. Within a sensitivity analysis uncertainties are evaluated. The impact of defined assumptions such as allocation rules, cut-off criteria, chosen impact categories can be evaluated and be adjusted. An LCA is an iterative approach [13].

Several LCAs, as well as PCF studies, exist for conventional steel production in literature. A literature review is included in this dissertation. For future steel production scenarios there is a lack of LCAs as well as PCFs. Without primary data metallurgical models are required to assess an LCA or PCF. Since the focus of metallurgical models in literature is generally on GHG emissions, PCFs are conducted for future scenarios in this dissertation. The focus is on BF related intermediate scenarios as well as DR plant-based steel production scenarios.

1.4 Research questions and connections of publications

The goal of this dissertation is to analyse the decarbonization of steel with PCF as main methodology. The BF route as well as the scrap based EAF route, which represent the state-of-the-art for steel production, are assessed with PCF. Additionally, scenarios towards climate neutral steel production routes are proposed and analysed. More in details, a stepwise transition from a coal-based metallurgy towards an electricity and hydrogen-based steel production is investigated. Steel production via DR plants combined with an EAF as well as combined with an electric melting unit and a BOF are in focus. The following research questions shall be addressed:

(1) What is the state-of-the art of LCAs for steel?

In a first step a literature review is carried out to present the state-of-the-art of LCAs for steel. The focus is on steel, produced via the BF route and the scrap-based EAF route as these account for more than 99% of global steel production [5].

(2) How is the recycling potential of steel evaluated in LCAs?

Steel is a material with a high recycling potential. The secondary steel production route is far less energy- and emission intensive than the primary steel production route. The evaluation of the recycling potential is intensively discussed in literature. In this dissertation several methodologies are described and recommendations are given.

(3) Which technologies can enable and push the transformation of the steel industry towards climate neutral steel production?

The decarbonization of the steel industry is a widely communicated goal. Intermediate scenarios can enable and accelerate this transformation. Four modifications of the BF route are analysed technically, and a PCF is conducted for these routes: (1) Injection of hydrogen in a BF, (2) injection of NG in a BF, (3) use of NG-based HBI in a BF, and (4) use of H_2-based HBI in a BF.

(4) How can steel be produced in a climate neutral way?

The focus of this dissertation is the technical analysis of DR-based steel production since the majority of European steel producers have declared this as the key technology for their transformation path. The use of DRI in an electric melting unit with further refining in a BOF as well as the use of DRI in an EAF are analysed in this dissertation. PCF assessments are conducted for these production scenarios.

(5) What impact does hydrogen and electricity production have on steel production?

Steel production can be based on hydrogen as reducing agent and electricity as energy supplier for the iron melting. Thus, hydrogen and electricity will become key inputs for future steel production and require special attention. PCF assessments for steel are conducted in function of different electricity and hydrogen production scenarios. Additionally, an energy analysis is carried out to assess how much electricity and hydrogen the future steel production will require as replacement for coal. Table 1 gives a survey on the research topics and the related publications.

Table 1: Research topics and publications

Research topic	Publication			
	I	II	III	IV
State-of-the-art of LCAs for steel	X			
Evaluation of the recycling potential of steel in LCAs	X			
Evaluation of intermediate scenarios towards climate neutral steel production. PCF assessments for H_2 and NG injection into a BF and use of NG-based and H_2-based HBI in a BF		X		
PCF assessments for DR-based steel production combined with an electric melting unit and a BOF			X	
PCF assessments for DR-based steel production combined with an EAF				X
Energy transformation of the steel industry. Shift from coal towards hydrogen and electricity			X	X

1.5 Structure of the dissertation

This dissertation consists of four chapters, see table 2. This chapter (introduction) introduces the research background of steel production, decarbonized steel production, and the LCA methodology. The motivation behind the dissertation is described in the research questions, and the linkage between the research topics and the four publications is outlined. These four publications are presented in chapter 2 (results). Key findings, challenges, and limitations are discussed in section 3 (discussion). Finally, a conclusion and an outlook for further research is given in section 4.

Table 2: Structure of this dissertation

1. Introduction
1.1 State-of-the art of steel production
1.1.1 Primary blast furnace relate steel production
1.1.2 Secondary steel recycling route via an electric arc furnace
1.2 Technical transformation of the steel industry
1.3 Life cycle assessments of steel
1.4 Research questions and connections of publications
1.5 Structure of dissertation
2. Results
2.1 Review of life cycle assessments for steel and environmental analysis of future steel production scenarios
2.2 Carbon footprint of scenarios towards climate-neutral steel production
2.3 Carbon footprint and energy transformation analysis of steel produced via a direct reduction plant with an integrated electric melting unit
2.4 Carbon footprint assessment of hydrogen and of steel produced via a direct reduction plant with an electric arc furnace (EAF)
3. Discussion
3.1 Key finding
3.2 Challenges
3.3 Limitations
4. Conclusion and Outlook
4 Conclusion and outlook

2 Results

This chapter presents the four publications of this dissertation. In each section the publication is first summarized and then the paper is attached.

2.1 Review of Life Cycle Assessments for Steel and Environmental Analysis of Future Steel Production Scenarios

This section presents publication I: 'Suer, J.; Traverso, M.; Jäger, N.: Review of Life Cycle Assessments for Steel and Environmental Analysis of Future Steel Production Scenarios. *Sustainability*, 14(21), 14131 (2022). https://doi.org/10.3390/su142114131', which addresses the research topics 1 and 2.

Publication I provides a literature review on LCA studies of steel produced via the conventional BF route and the scrap-based EAF route. In the LCA studies it was given particular attention to the evaluation of the recycling potential of steel. Methodological and technical assumptions of the LCA studies are explained in detail, so that the reader can properly assess why LCA results from literature can significantly differ for the current steel production.

Afterwards, innovative steel production routes are pointed out. A literature review is presented for the scenarios:

- The injection of H_2 in a BF
- The use of HBI in a BF
- Direct reduction of iron ores with subsequent electrical melting

The focus of the assessment of these technologies is on GHG emissions and related GWP as well as energy consumptions.

sustainability

Review

Review of Life Cycle Assessments for Steel and Environmental Analysis of Future Steel Production Scenarios

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Abstract: The steel industry is focused on reducing its environmental impact. Using the life cycle assessment (LCA) methodology, the impacts of the primary steel production via the blast furnace route and the scrap-based secondary steel production via the EAF route are assessed. In order to achieve environmentally friendly steel production, breakthrough technologies have to be implemented. With a shift from primary to secondary steel production, the increasing steel demand is not met due to insufficient scrap availability. In this paper, special focus is given on recycling methodologies for metals and steel. The decarbonization of the steel industry requires a shift from a coal-based metallurgy towards a hydrogen and electricity-based metallurgy. Interim scenarios like the injection of hydrogen and the use of pre-reduced iron ores in a blast furnace can already reduce the greenhouse gas (GHG) emissions up to 200 kg CO_2/t hot metal. Direct reduction plants combined with electrical melting units/furnaces offer the opportunity to minimize GHG emissions. The results presented give guidance to the steel industry and policy makers on how much renewable electric energy is required for the decarbonization of the steel industry.

Keywords: life cycle assessment; recycling; direct reduced iron; electric arc furnace; hydrogen

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Citation: Suer, J.; Traverso, M.; Jäger, N. Review of Life Cycle Assessments for Steel and Environmental Analysis of Future Steel Production Scenarios. *Sustainability* **2022**, *14*, 14131. https://doi.org/10.3390/su142114131

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1. Introduction

In order to prevent irreversible damage, global warming has to be kept well below 2 °C, preferably below 1.5 °C [1]. The energy-intensive steel industry is responsible for 7% of total world CO_2 emissions [2]. Furthermore, the absolute global CO_2 emissions are still increasing since the increasing steel consumption outweighs technological efficiency gains. Therefore, breakthrough technologies have to be implemented in order to reach the aforementioned environmental targets [3].

An overview of environmental sustainability in steel and cement production is given by Nidheesh et al. (2019) [4], Hasanbeigi et al. (2014), and Ariyama et al. (2019) present a technical review and solutions for a CO_2-reduced steel production [5,6]. Hasanbeigi et al. (2014) give special focus on alternative emerging technologies for a CO_2-reduced steel production [5]. Scenarios for the decarbonization of the European steel industry are given by Pardo and Moya (2013) [7].

In this paper, the environmental impacts of steel production are analysed and assessed using the LCA methodology. According to the international standards ISO 14040 and ISO 14044 [8,9], the LCA is an established standardized methodology to determine the environmental impacts of products. Thereby all phases of a product's life cycle from the extraction of raw materials, the manufacturing, the use phase, and finally the recycling process or the disposal of wastes should be included according to the so-called cradle-to-grave approach.

The LCA methodology, which is widely applied in literature, allows the assessment of the environmental impact of all kinds of products. An LCA study of the Chinese steel production is presented by Liang et al. (2019) [10]. Olmez et al. (2016) present an LCA study of steel production in Turkey [11]. The impact of mining is analysed by Koltun and Klymenko (2020) [12]. In chapter 2 and 3 further LCA studies of the steel production are presented.

Since an LCA study does not specify on a single product group, the rules defined in the ISO norms 14040 and ISO 14044 allow its practitioners freedom for certain purposes. Strict rules, which would be useful for one product group, could be counterproductive for another one. The allocation of co-products and recycling materials are prominent examples for which the ISO norms allow its practitioners freedom. In the case of steel, several environmental allocation approaches have been applied for the primary and secondary steel production. Since different approaches have a strong influence on the LCA results, an overview of the most common approaches is given in this paper (Section 2).

Although there are several reviews about the environmental impact of the steel production within the literature, there is a lack of reviews of LCA studies. This paper fills this gap by presenting several LCA studies and by discussing some methodological and technical assumptions (Section 3). This will help the reader to properly assess why the LCA results from the literature for the current steel production can significantly differ.

On this basis, breakthrough technologies for a decarbonized steel production are presented. As interim scenarios, modifications of the blast furnace related steel production route are presented like hydrogen injection into the blast furnace (BF) or use of pre-reduced iron ores in the BF (Section 4). Since the decarbonization cannot be fulfilled completely within the BF route [13], the steel production via direct reduction (DR) plants is also presented (Section 5). DR plants in combination with electrical melting offer the opportunity to minimize GHG emissions. The DR technology is fully developed and commercially available, thus it can enable the transformation process in time [14,15]. The overview in this paper provides a good estimation of the amount of renewable electric energy which is required for the decarbonization of the steel industry.

For this literature review the databases Web of Science, Scopus, and the search engine google scholar were used. Typical used keywords were: life cycle assessment; carbon footprint; environment; steel; direct reduction; electric arc furnace; hydrogen; carbon direct avoidance; and recycling. Literature from the year 2000 onwards is integrated into this review.

The goal of this study is to present an LCA overview of the current steel production and to analyse future scenarios which can enable a decarbonized steel production.

2. Environmental Allocation Approaches for Primary and Secondary Steel Production

Steel is produced primarily from iron ores or secondarily from scrap recycling. The primary blast furnace–basic oxygen furnace (BF–BOF) route is currently the world's most used production route with a share of about 73% in the year 2020 [16]. Yet the primary route is not completely primary, since, within the refining process of converting hot metal to crude steel, scrap is used as a cooling material. About 26% of the steel is produced via the scrap-based EAF recycling route [16]. In sum, 32% of steel is produced from scrap input via the secondary route and partially via the primary route [2]. Within the primary production route, reduction work is required to reduce the iron oxides and the gangue has to be separated from the iron ores. This is not required in the scrap-based steel production. Thus, the BF–BOF route's average primary energy demand is about 23 GJ per tonne of crude steel (CS) whereas the scrap-based EAF route's energy demand is about 5.2 GJ/t CS [2]. The direct and indirect carbon dioxide emissions for the BF–BOF route are about 2.2 t CO_2/t CS and about 0.3 t CO_2/t CS for the scrap-based EAF route [2].

An ISO 14040/44 conform LCA considers the whole life cycle from cradle-to-grave, meaning that primary and secondary steel production are not considered separately, since both processes belong to the life cycle of a steel product. Yet, since the use phases of steel are numerous, a cradle-to-grave analysis is, in general, not practical for the product steel. A common solution is to provide a cradle-to-gate approach including the processes from the raw material supply to the product, which leaves the plant gate, e.g., steel. A complete life cycle approach is consciously reduced. When primary and secondary production are separated from each other by the chosen system boundaries, the issue is this: Should the primary steel producer carry the burden of the energy- and emission-intensive production alone or should it be shared with the secondary steel producer? Every kind of scrap, which is recycled in an electric arc furnace, has once been produced by the primary route. At first glance, this question may seem to be just a theoretical allocation problem, but LCA studies have an increasing impact on political and market economy decision-making. Several recycling methodologies have been discussed in the last decades to solve this problem and it will be discussed here in the following paragraphs.

The common intersecting set of primary and secondary steel production is the steel scrap. Whereas the primary steel producer delivers a net scrap surplus, the secondary steel producer consumes this generated scrap. The World Steel Association (WSA) delivers two methodologies that focus on the evaluation of steel scrap [17]. This methodology is based on the principles explained in a worldsteel methodology report of the year 2000 [18]. The approach is described for the carbon footprint of steel by the WSA [17], but it applies for all impact categories.

- The recycled content approach: The scrap does not have an environmental burden, which means neither an environmental footprint is taken into account when scrap is used nor the recycling credit at the end-of-life is considered.
- The end-of-life recycling approach: Scrap has an environmental footprint. Therefore, an environmental burden has to be considered when scrap is used, and credit is given when the material is recycled at the end-of-life.

It is obvious that by the end-of-life recycling approach, the LCA impact of the primary steel reduces in comparison to the recycled content approach since an environmental credit for the net scrap production is given. On the contrary, the LCA impact of the secondary steel increases since the net scrap acquisition carries an environmental burden. The LCA impact of scrap is defined in such a manner that the LCA impact of primary and secondary steel, following the end-of-life recycling approach, is per definition equal [17].

The principle of equating the LCA impact of primary and secondary steel following the end-of-life approach has been intensively discussed within literature. Within the WSA Report [17] and a declaration by the metals industry on recycling principles [19], a clear commitment is announced to support the end-of-life recycling approach over the recycled content approach, referring to the following reasons:

- The demand of scrap is far above the supply. Scrap has a high economic value, which means that where scrap is recovered it will be used for recycling. Consequently, there is no need to additionally create a demand for recycled material since this market is already mature. For metals where there is a limited supply of recycled feedstock, market stimulation is ineffective and may result in inefficient processing and unnecessary transportation.
- Steel has inherent properties so it can be recycled almost an unlimited number of times. Although, in general, within the primary steel production routes, higher steel grades can be produced in comparison to the secondary steel production route, secondary steel production replaces primary steel production. As long as the scrap is recycled and the products are in demand, it does not matter in which area of application the steel is used.
- The demand of steel scrap exceeds the availability. Since the scrap cannot fulfil the sector's raw material input, primary steel production is still a necessity [17,19].

In the year 2020, globally, between 80–90% of the steel is recycled, and around 70% of it is produced from iron ores, primarily proving that the line of reasoning is still present [2].

The discussion about the evaluation of the recycling potential of steel continued since the beginning of the new millennium.

Birat et al. (2006) described that an LCA offers its practitioners ample freedom on choosing how they take recycling into account [20]. Therefore, they developed six mathematical models for evaluating the recycling potential. The first approach is the simplest approach: ignoring the recycling issue. They do not recommend this approach, since 'recycling is already being carried out today at a very high level'. The other five recycling approaches combine physical- and economical-based aspects. Thereby one-step and multi-step recycling approaches are developed.

Neugebauer and Finkbeiner (2012) developed a multirecycling approach by reproducing the life cycle of steel [21]. One tonne of hot-rolled coil is produced primarily via the BF route and infinitely times recycled in an EAF. They considered mass losses during the use phases and the recycling processes. The environmental burdens are added over the life cycle and are shared equably.

In 2013, the European Commission published the "Product Environmental Footprint (PEF)" with the aim of harmonising LCA rules. Within 25 pilot projects, product specific rules were defined (Product Environmental Footprint Category Rules(PEFCR)), amongst them the PEFCR for metal sheets for various applications [22]. The calculation of the recycling potential was strictly predetermined by a circular footprint formula (CFF). An allocation factor defines how the recycling potential is weighted from 0.2 (high recycling potential) to 0.8 (low recycling potential). For metal sheets the allocation factor was set on 0.2 so that a maximum recycling potential was considered within the defined range [23].

Despite several recycling methodologies being evolved, a consensus was not found in the last two decades. Frischknecht (2010), Yellishetti et al. (2011), Reale et al. (2015), and Mengarelli et al. (2016) stated that no consensus has been achieved on how to model recycling in LCA [24–27]. Frischknecht (2010) stated that it is unlikely that a consensus will ever be found [24].

Nevertheless, currently it is highly discussed within the EU, which attributes a common 'green steel' must have. Therefore, the methodology of evaluating the recycling potential gains again is of much importance. If no global perspective is followed for the definition, but only the emissions of a specific steel producer are crucial, it might be easier for steel producers to shift partially from primary to secondary steel production than implementing breakthrough technologies within the primary route.

For metals with limited supply of recycled feedstock, external market stimulation is ineffective and may result in inefficient processing and unnecessary transportation, as Volkhausen (2003), Atherton (2006), Birat et al. (2006), Larsson et al. (2006), and WSA (2011) stated [17,19,20,28,29]. The decarbonization of the global steel industry can only be achieved by breakthrough technologies of the energy-intensive primary steel production route. An effective definition of a common 'green steel' must take into account the recycling potential, so that breakthrough technologies are promoted and not a shift from primary to secondary production. Even until 2050 the scrap share of metallic input will only be around 50%, since the increasing demand cannot be filled by scrap recycling alone [2,30,31]. In the following chapters, possible solutions for decarbonizing the steel industry are presented.

3. Life Cycle Assessment (LCA) of State-of-the-Art Steel Production Routes

In the following chapter, LCA studies for the state-of-the-art primary steel production via the BF route and for the secondary recycling route via an EAF are presented. Methodological as well as technical differences are analysed and their impacts on the results.

3.1. LCA Overview of the Primary Blast Furnace-Related Steel Production Route

The BF–BOF route is the world's most dominant steel production route with a share of 73% in 2020 [16]. A simplified chart is presented in Figure 1. The iron oxides are reduced and melted by pulverized coal and coke in a BF. As supporting processes, fine iron ores are pelletized and sintered, respectively, to be used in the BF. The feedstock for the BF must not be too fine to ensure sufficient gas permeability in the shaft furnace. Another supporting process is the pyrolysis of coal to coke in a coke plant. Besides serving as a reducing agent and energy supplier, coke serves as a supporting matrix, also to ensure gas permeability in the BF.

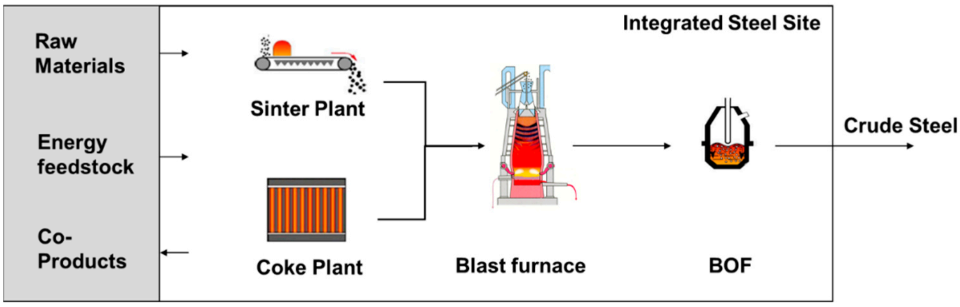

Figure 1. System boundary of an integrated steel site.

An overview of environmental LCA studies of the products steel produced over the BF–BOF route is presented in the following. Some studies consider the flat steel product hot-rolled coil (HRC), which is produced from steel slabs in a hot-rolling mill. The main messages and results are afterwards summarized in Table 1.

Norgate et al. (2007) [32] reported an LCA about the metals nickel, copper, lead, zinc, aluminum, titanium, and steel from the BF–BOF route, and stainless steel from the scrap-based EAF route. Assessing the system from cradle-to-gate, Norgate et al. included the processes from raw material mining, sinter plant, BF, and BOF in case of the metal steel. There is no information on whether steel scrap has an environmental burden and how the co-products like the BF slag and BOF slag are evaluated. They investigated the environmental impact categories of global warming potential (GWP) and acidification potential (AP).

Neugebauer and Finkbeiner (2012) [21] presented a multirecycling approach of steel. Primarily produced HRC is five times recycled within an EAF and the environmental burdens are shared equally over the life cycles. Losses during the use phase and the recycling process are considered. Credits for the co-products BF slag, BOF slag, electricity, benzene, sulphur, and tar are given. The results of the study presented in Table 1 prove that the choice, whether the recycling potential is taken into account or not, has crucial effect on the LCA results. The data are based on the German industry.

Burchart-Korol (2013) [33] presented an LCA of the steel production in Poland considering both the BF–BOF route and the EAF route. The data are averaged from existing steel plants in Poland. A cradle-to-gate system is used. An environmental burden of scrap is not mentioned and is most likely not considered according to the results, which are presented. Comparably high credits for BF and BOF slag are given, e.g., the GWP presented without credits for the slag is 2.5 kg CO_2 eq/kg steel and the GWP including the slag credit is 1.7 kg CO_2 eq/kg steel, see Table 1.

Within an Italian LCA study special attention is given to the human toxicity aspects of single processes from an integrated site [34]. This LCA uses the cradle-to-gate system, including the processes from raw material mining up to the product steel slab. The data have different sources: industry, literature, and commercial LCA databases. The GWP presented of 1.6 kg CO_2 eq per kg of steel is quite low in comparison to the other results from literature, see Table 1. The results from the LCI reveal that a coal input is composed of 0.58 kg/kg steel into the coke plant and 0.16 kg/kg steel as pulverized coal into the BF. Considering an emission factor of about 3.0 kg CO_2/kg coal [35], the coal input would lead to 2.2 kg CO_2/kg steel. Parts of environmental impacts are allocated to the by-products BF gas, Coke plant gas, BOF gas, and BF slag, amongst others. An allocation method considering both the mass and economic value was assessed. A consideration of an environmental burden of scrap is not mentioned.

Chisalita et al. (2019) [36] assessed the environmental impact of an integrated steel site and evaluated the potential of CO_2 capture and storage using the LCA methodology. The data are based on a report of the IEA [37]. Emissions from the manufacture of purchased pellets, burnt dolomites, and scrap are not included. Despite an amount of probably 0.57 kg coal per kg of HRC (Within the LCI 568.69 t coal/t HRC is presented. The authors of this paper assume that it was a mistake, and it should have been kg coal instead of tonnes coal per tonne HRC) presented within the LCI, the abiotic depletion potential of fossils (ADPf) is only 5.3 MJ/kg HRC, see Table 1. Considering a lower heating value (LHV) of 32 MJ per kg of coal [35], this ADPf is questionable. The use of a biomass-based coal is not mentioned. Credits for co-products are not included.

Backes et al. (2021) [38] reported an LCA about a primary German BF–BOF route. A cradle-to-gate approach is used including the processes from raw material supply up to the product HRC. The data are based on the German industry. Credits for co-products are given. An environmental burden for scrap is not given following the recycled content approach.

The results of the aforementioned LCA studies are summarized in Table 1.

Table 1. Overview of life cycle assessments (LCA) studies for a blast furnace related steel and hot-rolled coil production.

Study	Year	Product	Methodology			Impact Categories			
		kg	Scrap	Co-Products	Impact Method	GWP kg CO_2 eq	AP kg SO_2 eq	ADPf MJ	CED MJ
[32]	2007	Steel	n. s.	n. s.	n. s.	2.3	0.020	n. a.	23
[21]	2012	HRC	MRA	SE	CML 16	1.0	3.0×10^{-3}	12	15
[21]	2012	HRC	RC	SE	CML 16	1.7	4.0×10^{-3}	24	24
[33]	2013	Steel	n. s.	SE	Recipe Midpoint	1.7	5.0×10^{-3}	n. a.	25
[34]	2016	Steel	n. s.	Allocation	ILCD	1.6	n. a.	n. a.	23
[36]	2019	HRC	RC	n. s.	CML 16	2.1	1.6×10^{-4}	5.3	n. a.
[38]	2021	HRC	RC	SE	CML 16	2.1	4.8×10^{-3}	21	n. a.

Abbreviations: HRC (Hot-rolled coil); MRA (Multi Recycling Approach); SE (System Expansion); RC (Recycled Content); GWP (Global Warming Potential); AP (Acidification Potential); ADPf (Abiotic Depletion Potential for fossil resources); CED (Cumulative Energy Demand); CML (Centrum for Milieukunde); n. s. (not specified); n. a. (not available).

The LCA results for steel can differ significantly depending on the underlying methodologies and assumptions. The choice of whether the recycling potential of steel is evaluated has a crucial effect. In the cases in which the scrap methodology is not specified, the authors of this paper assume that the scrap is not evaluated following the recycled content approach. In addition, the methodologies and databases chosen for evaluating the co-products, which are in particular the BF slag, the BOF slag, the process off-gases, and surplus electricity from integrated power plants have significant impact on the results. In general, the chosen life cycle impact assessments (LCIA) methods might also lead to differences in case study results, as Bach and Finkbeiner (2017) demonstrated at the example of the impact categories AP and eutrophication potential (EP) comparing the CML (Centrum for Milieukunde) method, the ReCiPe method, and the method of accumulated exceedance [39]. In case of steel, the differences between the CML method and the ReCiPe method are quite moderate for the impact categories GWP, AP, and ozone depletion potential (ODP) [21].

Besides methodological differences, the results of case studies depend on the process control, which shall be explained in the example of the impact category of climate change. The amount of scrap used in the BOF has a significant environmental impact, in particular, if the scrap is not evaluated with an environmental burden. Scrap replaces hot metal in the BOF. Since the production processes until hot metal are the most GWP-intensive ones, a replacement of hot metal has a high impact on GWP reductions. In the BF the iron feedstock graded sinter, iron ore pellets, and lump ore can be used. The upstream environmental impacts of these input materials differ significantly and thus have influence on the carbon footprint of the resulting hot metal and steel.

The production step from steel to HRC requires fuel consumption between 1.3 and 1.4 MJ/kg HRC [40,41]. Regarding the direct and indirect GHG emissions from natural gas and electricity consumption Kahlid et al. (2021) [40] report 0.11 kg CO_2 eq/kg HRC due to hot rolling [40]. An increased steel production due to losses within the hot-rolling process is not considered. However, this gives a range of the difference caused by the two various products listed in Table 1. In addition, different assumptions regarding to the use of alloying elements have an impact on the results.

Steel is made from natural raw materials, which differ in their quality. The better the quality of the feedstock, the higher the metallurgical advantages, e.g., for every 1% increase in iron (FE) content of the iron ores, there is a 1–3% increase in productivity and a similar decrease in coke rate. The ash, sulphur, and phosphorous contents are important for the used coal. The ash is the inorganic residue after burning and consists of refractory oxides as SiO_2, Al_2O_3, Fe_2O_3, and CaO, amongst others. To transfer the ash, the sulphur, and the phosphorous of the coke into the slag within the BF process, energy in the form of coke and coal and slag building components are required. For a 1% increasing of ash, there is a productivity decrease of 2–3% and a coke rate increase of 1–2% [42].

3.2. LCA Overview of the Secondary Scrap-Based Steel Production Route

Besides primary steel production from iron ores, steel can be produced via scrap recycling. Globally, about 26% of steel is produced via the scrap-based electric arc furnace (EAF) route in year 2020 [16]. In an EAF, scrap is melted by electrodes via an electric arc, see Figure 2. Carbon and oxygen are added to form a foaming slag. The foamed slag infolds the electrodes, and thus it reduces radiation losses and protects the refractories. In addition, lime is added to improve the foaming properties of slag and to bind undesirable components in the slag [43].

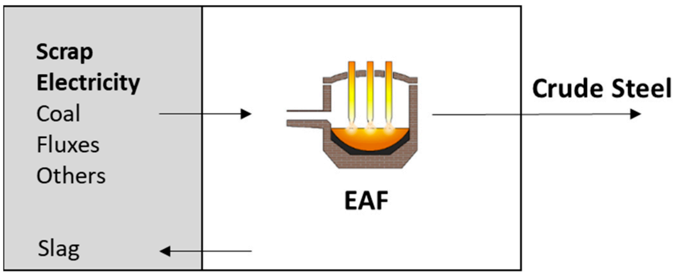

Figure 2. System boundary of an EAF-based recycling steel production.

In the following, a literature overview on LCA studies of a scrap-based steel production via an EAF is presented.

Neugebauer and Finkbeiner (2012) presented, as part of a multirecycling approach, an LCA for a scrap-based EAF production for the product HRC [21]. Thereby a cradle-to-gate approach was followed. Within the results presented in Table 2, the scrap is not evaluated. The electricity input for the EAF has a major impact on the impact categories GWP, AP, ADPf as well as on the CED. A German grid mix is assumed in the study. Credits for co-products are not given [21].

Burchart-Korol (2013) analysed the Polish steel production via an EAF following the LCA methodology [33]. Within a cradle-to-gate approach, several impact categories were evaluated for the product crude steel, some of which are listed in Table 2. An environmental burden of scrap is not mentioned and is most likely not considered in regard to the results presented for the EAF route. The cumulative energy demand (1.3 MJ/kg) is quite low considering the fact 1.5 MJ/kg of electricity is required for the EAF [33]. About 6.8 MJ/kg steel credit is given for the EAF slag. Without this credit, the CED would be 8.1 MJ/kg steel. Furthermore, the GWP would be 0.91 kg CO_2 eq/kg steel without considering a credit for the EAF slag.

Table 2. Overview of life cycle assessment (LCA) studies for an EAF produced steel and hot-rolled coil production.

Study	Year	Product	Methodology			Impact Categories			
		kg	Scrap	Co-Products	Impact Method	GWP kg CO_2 eq	AP kg SO_2 eq	ADPf MJ	CED MJ
[21]	2012	HRC	RC	n. a.	CML 16	0.74	0.0020	7.5	11
[33]	2013	Steel	n. s.	Credit for EAF Slag	Recipe Midpoint	0.77	0.0025	n. a.	1.3

Abbreviations: HRC (Hot-rolled coil); RC (Recycled Content); GWP (Global Warming Potential); AP (Acidification Potential); ADPf (Abiotic Depletion Potential for fossil resources); CED (Cumulative Energy Demand); n. a. (not available); n. s. (not specified).

Norgate et al. (2007) presented an LCA for stainless steel from an EAF [32]. The GWP is 6.8 kg CO_2 eq/kg steel following a cradle-to-gate approach. Due to the high share of alloying elements, stainless steel is not considered in this comparison.

The environmental impact of steel production benefits from its recycling potential, which is clearly pointed out within the multirecycling approach by Neugebauer and Finkbeiner (2012) [21]. End-of-life scrap can be reused by melting it nearly infinite times. Comparing Tables 1 and 2, it becomes apparent that the process of scrap recycling is significantly less energy and emission intensive than the primary steel production. With regard to the transformation of the global steel industry towards climate neutrality, it is important that secondary steel production will be continued but there is no global benefit if a single steel producer shifts from primary to secondary steel production. For decarbonizing the secondary steel production, most of all the national electricity mixes have to be decarbonized by increasing the share of renewable electric energies.

The results also show that the availability of LCAs about secondary steel production are quite rare.

4. Modifications of the Blast Furnace Steel Production Route

The BF is the most energy and CO_2 emission-intensive process of the BF route, in which the iron oxides are reduced and melted to hot metal. About 420 kg carbon per tonne of hot metal (HM) are required. This carbon input leads to carbon dioxide emissions of 1.5 kg CO_2/kg HM [35]. The carbon input is almost exclusively delivered by coke and coal. In the following two alternative BF operation modes are presented. The first aims to partially replace coal by hydrogen as a reducing agent and energy carrier. The second aims to replace the feedstock iron oxide by reduced iron ore in the form of hot-briquetted iron (HBI).

The literature for these metallurgical scenarios focuses on carbon dioxide emissions. Thus, in the following chapter the focus is also on CO_2 emissions.

4.1. Use of Hydrogen in a Blast Furnace

In addition to coke, alternative reducing agents (ARA) can be injected into a BF for both reduction and energy supply. About 65% of the BFs worldwide use injection technology. Thereof 75% of the BFs operate with pulverized coal (PC) [44]. As replacement for coke, a theoretical maximum for coal injection is thought to be 270 kg/t HM [45]. Indeed, Lüngen and Schmöle (2020) [46] reported within a comparison of BF operation modes worldwide a maximum coal injection rate of 250 kg/t HM and a lowest coke rate of 260 kg/t HM. Babich (2021) gave a recent survey of the injection of selected ARA, such as pulverized coal, biomass products, and hydrogen containing gases—natural gas, coke oven gas, and hydrogen—with the aim of reducing CO_2 emissions [44].

From a metallurgical perspective, beside carbon, hydrogen is also able to reduce the iron oxides inside the BF [47,48].

$$Fe_2O_3 + 3\ H_2 = 2\ FE + 3H_2O \quad (1)$$

The equilibrium reduction reactions of iron oxides with hydrogen and carbon monoxide, respectively, as a function of the temperature are described in a Baur-Gläsner diagram [47]. Although a partial shift from carbon towards hydrogen can be achieved within a BF, the coke cannot be completely replaced since it is required as a supporting matrix in order to ensure gas permeability inside the shaft furnace. Figure 3 shows the material streams for hydrogen injection into a BF in a simplified scheme.

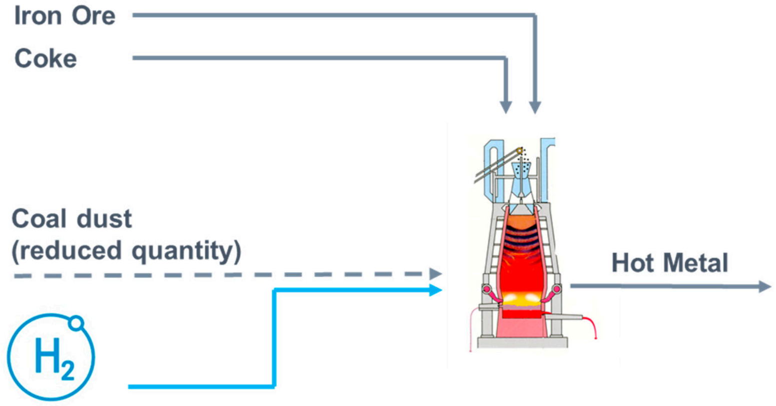

Figure 3. Injection of hydrogen into a blast furnace.

The shift from carbon towards hydrogen has some metallurgical consequences, which require attention. Whereas in sum, the reduction of iron ores by carbon monoxide is exothermic, the reduction by hydrogen is endothermic [49,50]. As a logical consequence, Bernasowski (2014) observed within a thermochemical simulation that the reduction with carbon monoxide is stronger at low temperatures, whereas the reduction with hydrogen is stronger at high temperatures [51]. Spreitzer and Schenk (2019) drew the conclusion that the addition of hydrogen is only useful to a certain extent since higher hydrogen contents lead to a higher energy demand. Within a BF, increased energy demand cannot solely be provided by the reaction of hydrogen with external oxygen. On the one hand, the resulting vapour decreases the reduction rate of the iron oxides by hydrogen drastically and on the other hand a solid supporting matrix out of coke is required to ensure the permeability in the shaft furnace [49]. A metallurgical advantage of hydrogen is its faster reduction rate than that of carbon monoxide because the diffusion potential of hydrogen is much higher than the diffusion potential of carbon monoxide. Hydrogen has a lower molecule size and viscosity compared to carbon monoxide [49].

Yilmaz et al. (2017) investigated the impact of the hydrogen's injection temperature on the coke reduction potential [52]. The operation of the base case was defined with a consumption of 500 kg coke per ton of HM. The reduction potential increases significantly with increasing temperature of hydrogen. With the low injection temperature (80 °C), the efficiency of hydrogen to replace coke decreases above 5 kg H_2/t HM. Above 20 kg hydrogen, the amount of coke even increases since additional heat is required in order to maintain the thermal state of the furnace. Due to the high specific heat capacity of hydrogen and the endothermic reduction, the adiabatic flame temperature (AFT) decreases. This can be counteracted by preheating the hydrogen. Yilmaz et al. (2017) reported for an optimal operation of 27.5 kg H_2/t HM with an injection temperature of 1200 °C and a carbon dioxide reduction potential of 289 kg CO_2/t HM [52]. Thereby, only the BF operation is within the system boundary.

In addition to Yilmaz et al. (2017) [52], Schmöle (2016) [53] considered the potential of hydrogen injection to reduce CO_2 emissions. Schmöle (2016) reported a 40 kg H_2/t HM a CO_2 reduction of 292 kg CO_2/t HM also considering only the BF operation [53]. Schmöle (2016) did not assume the preheating of the hydrogen, so it is plausible that Schmöle (2016) reported a higher hydrogen consumption for nearly the same reduction potential as Yilmaz et al. (2017) did [52].

De Castro et al. (2017) investigated within a numerical simulation the injection of pulverized coal combined with hydrogen, oxygen, and carbon dioxide into a BF [54]. In combination with hydrogen and oxygen, the injection of carbon dioxide can be an advantage in order to reduce carbon dioxide emissions. For an injection of 20 kg H_2/t HM (A hydrogen density of 0.0899 kg/m^3 is assumed within this paper) de Castro et al. (2017) reported an emission reduction of 100 kg CO_2/t HM (De Castro et al. [54] reported a specific carbon emission. These emissions are multiplied by 44/12 within this paper to consider the mass addition from C to CO_2). In this case, no preheating of hydrogen was assumed, and no CO_2 was injected. With an additional CO_2 injection of 56 kg/t HM (A CO_2 density of 1.977 kg/m^3 was assumed within this paper), de Castro et al. (2017) reported for a hydrogen injection of 13 kg/t HM, an emission reduction of 182 kg CO_2, if the injected CO_2 is also considered as a sink [54].

In addition to the ability of hydrogen to reduce carbon within the BF process, the production of the hydrogen has to be taken into account as well for a fair comparison. Mehmeti et al. (2018) presented an LCA of hydrogen from conventional to emerging technologies [55]. The carbon footprint of hydrogen lies within a range between 2.2 kg CO_2 eq/kg H_2 for an electrolysis process driven by wind power and up to 29.5 kg CO_2 eq/kg H_2 for an electrolysis process driven by a national Italian grid mix. If the hydrogen origins from fossil fuels the total impact on climate change can even be significantly increased when injecting hydrogen into a BF.

In Figure 4 the GHG emissions resulting from the hydrogen supply from electrolysis driven by wind power of 2.2 kg CO_2 eq/kg H_2 are converted in kg CO_2/t hot metal regarding to the different hydrogen injection rates presented in the studies. In addition, the carbon dioxide emission savings reported in the literature for hydrogen injection are presented.

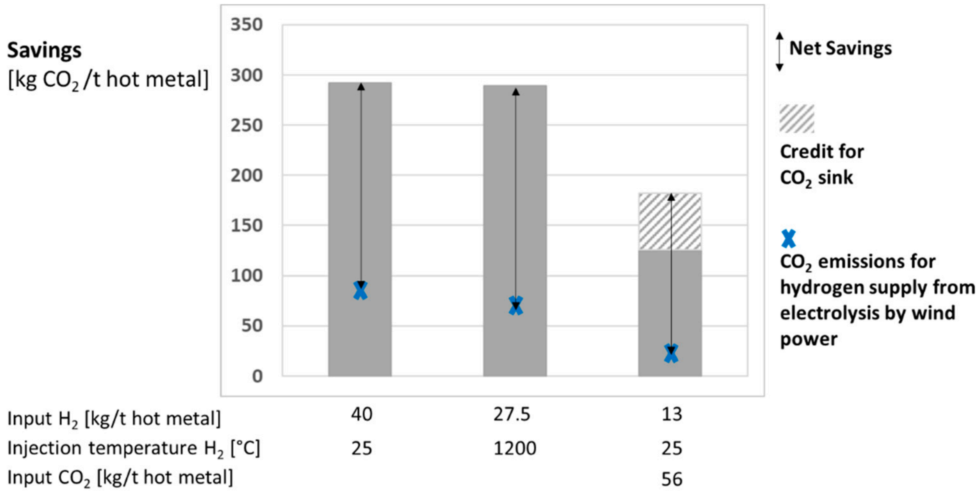

Figure 4. Carbon dioxide emission savings for injection of hydrogen into a blast furnace [52–55].

The simulation results of the different authors do not give a clear, single statement. However, it has to be taken into account that the BF and especially the raceway is a very complex system consisting of combustion-, Boudouard-, water gas shift-, and reduction reactions, amongst others, which interact with each other. Different assumed boundary conditions can have a major impact on the simulation results. It is questionable, for example, if the hydrogen oxidises directly after the tuyéres or if it is possible to bring in the hydrogen deeper into the furnace so that the hydrogen is used directly for the reduction of the iron ores. If the hydrogen is directly oxidised to water vapour after the tuyéres, the expansion will increase the pressure, which will complicate the injection of the blast.

De Castro et al. (2017) reported, for example, an increased raceway temperature as result of H_2 combustion [54]. Yilmaz et al. (2017) stated that the adiabatic flame temperature (AFT) is reduced with the hydrogen injection because of the high specific heat capacity of hydrogen [52]. The endothermic reduction of hydrogen with iron ores also indicates that the AFT is expected to decrease the hydrogen that does not directly oxidise after the tuyéres but is able to reduce the iron ores. Only practical field tests can give clear guidance and would improve the data quality.

Likewise, the injection of hydrogen into a BF, the injection of natural gas [56–58], or coke oven gas [59] are also options for a modified BF operation. All these scenarios aim to partially replace carbon by hydrogen input. Other circular-based options are the use of biomass [60] or, e.g., the use of waste plastics [61,62] in the BF.

4.2. Use of Pre-Reduced Iron Ores in the Blast Furnace

A partial replacement of iron oxides by pre-reduced iron ores diminishes the carbon input into a BF, since less reduction work is required [47].

$$Fe_2O_3 + 3\ H_2 = 2\ FE + 3H_2O \quad (2)$$

Thus, the BF functions more as a melting unit than as a reduction unit [53]. The reduction process is shifted to an upstream process. DR plants offer an established technology to produce pre-reduced iron ores. Thereby the iron ore is reduced to direct reduced iron (DRI). The reduction takes place exclusively within the solid phase and there is no melting. In a shaft furnace operation, various gases can be used as sources of the reducing the gases hydrogen and carbon monoxide: natural gas, hydrogen, coke oven gas (COG), basic oxygen furnace gas (BOFG), etc. [63].

The DRI is porous and the resulting high surface to volume ratio harbours the risk of re-oxidation in the air. In the presence of water, the DRI can oxidize quickly with the formation of hydrogen. The porous structure of the DRI can complicate the handling, storage, and transport of the product [64]. That is why the briquetting of DRI to HBI (hot briquetted iron) is the usual way to reduce the surface to volume ratio. Especially if using the DRI/HBI in a BF, it is reasonable to insert it in a briquetted form so that re-oxidation in the upper shaft areas of the BF with higher oxygen partial pressures can be avoided [65].

For evaluating the environmental impact of using HBI in a BF, the effect on the BF and on the process of direct reduction has to be taken into account. In the following, literature about the DR process and about the changes of a BF operation with HBI are presented.

Yilmaz and Tureka (2017) considered a natural gas and hydrogen based direct reduction in a shaft furnace [66]. The total energy demand of the DR plant is between 8.6 GJ/t DRI for a hydrogen-based operation and 10 GJ/t DRI for a natural gas-based operation. Four different types of DRI are compared whose main distinguishing characteristic is the different carbon content. The range of the DRI's C-content is between 0.5% and 4%. The DRI is carburized by natural gas injection. Thus, for a hydrogen-based operation between 0.34 GJ/t DRI and 1.3 GJ/t DRI, natural gas is injected leading to carbon contents of 0.5 to 2.0% C in the DRI. Yilmaz and Tureka (2017) reported CO_2 emissions of 410 up to 500 kg/t DRI for natural gas-based reduction [66]. For a completely hydrogen-based operated DR plant the emissions can be nearly zero.

The higher the C-content of the DRI, the more energy input is required. The formation of the injected carbon into carbide (Fe_3C) is endothermic [67]. Yet, the carbide is bond energy and lessens the energy requirement of the subsequent melting process [64].

Since the DRI is only reduced within the DR plant and not melted, it still contains the gangue. For removing the gangue, the DRI has to be melted electrically or as interim scenario it can be added with the iron ores inside a BF and get melted by coal and coke.

Schmöle (2016) [53] modelled the use of 400 kg HBI/t HM in a BF and reported an emission reduction of 377 kg CO_2/t HM, see Figure 5. A similar result was investigated in a modelling and simulation approach by Yilmaz and Tureka (2017) [66]: For the use of 400 kg HBI/t hot metal, they reported an emission reduction of 361 kg CO_2/t hot metal regarding the BF process. It was found that the fuel rate decreases until 400 kg HBI/t hot metal in a linear correlation. The emissions concerning a natural gas-based DR plant, which are reported by Yilmaz and Tureka (2017) are also integrated in Figure 5 [66]. An averaged emission value of 455 kg CO_2/t DRI is assumed.

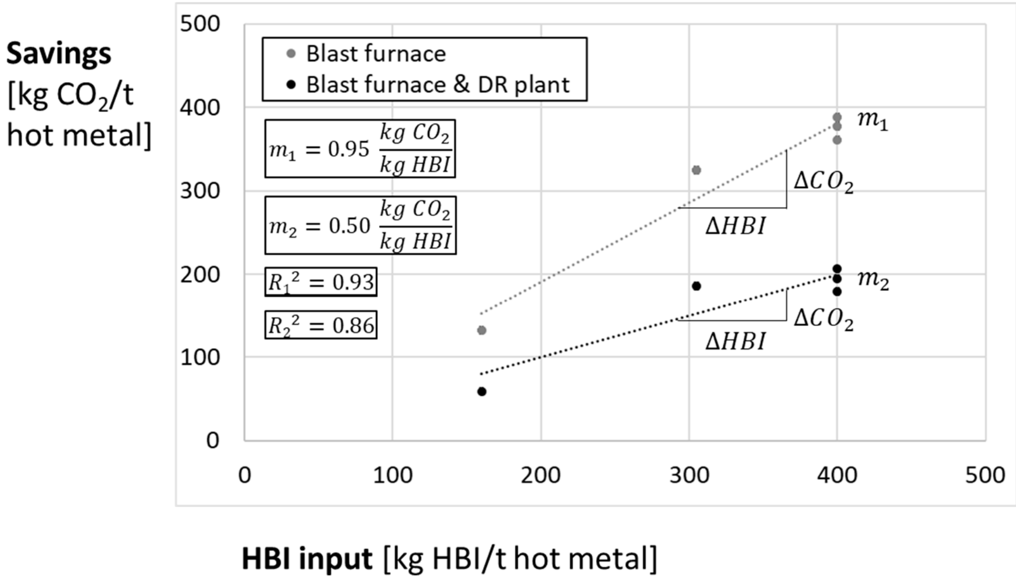

Figure 5. Carbon dioxide emission savings for HBI input in a blast furnace. The upper line describes the CO_2 savings of the blast furnace process. The lower one also includes the emissions of a natural gas-based DR plant [53,66,68–70].

Müller et al. (2018) presented 388 kg CO_2/t HM (This emission reduction is calculated from the absolute emissions savings and the emissions of the DR plant reported by Müller et al. (2018) [68]) savings for the use of 400 kg/t of HBI derived from a modelling approach [68]. They also included the emissions of the DR plant, which are 415 kg CO_2/t DRI, which fits to the range reported by Yilmaz and Tureka (2017) [66].

Griesser and Buergler (2019) presented primary data from a field test [69]. The maximum HBI input was 160 kg/t hot metal. They reported that per 100 kg HBI the reducing agent rate (coke equivalent) can be decreased by 25 kg/t HM. Assuming an emission factor of 3.3 kg CO_2/kg coke [35], the input of 160 kg HBI/t HM leads to a decrease of 132 kg CO_2/t HM.

Kobe Steel (2021) inserted up to 305 kg HBI/t HM in a BF [70]. They reported a reduction of reducing agents of 103 kg/t HM. The share of coke and coal reduction is not reported, so assuming emission factors of 3.0 kg CO_2/kg coal and 3.3 kg CO_2/kg coke [35], the HBI input leads to a carbon dioxide reduction from 309 to 340 kg CO_2/t HM for the use of 305 kg HBI/t HM. In Figure 5, an average value is assumed for the reported emission savings.

The CO_2 reduction potential of the BF operation is about 0.95 kg CO_2/kg HBI (Figure 4, m1). Considering the emissions of the natural gas-based DR plant the CO_2 reduction potential is about 0.50 kg CO_2 per kg HBI use in a BF (m_2).

The different CO_2 reduction potentials concerning the BF process presented in the literature could have resulted from different assumed C-contents of the inserted HBI. A higher C-content reduces the external carbon input in the form of coal and coke in an effective way [64]. In sum, the high R-squared values demonstrate that the CO_2 emission savings can be described by a linear function in dependency of the HBI input quite well.

The use of HBI also changes the upstream impacts of a BF operation. Less coal, coke, and iron feedstock like lump or and iron ore pellets are required. Yet, the production of HBI also causes an upstream impact. A DR plant typically is fed with iron ore pellets or alternatively lump ore and natural gas is used as reducing agent. These upstream impacts are not considered in Figure 5. A comprehensive carbon footprint assessment is done by Suer et al. (2021) [71].

5. Direct Reduced Iron (DRI) Production with Electrical Melting

DR plants offer an alternative way to reduce iron oxides, see Section 4.2. In contrast to a BF operation, the reduction can be based completely on gases like natural gas, coke oven gas, and pure hydrogen, amongst others [63]. Since the iron ores are not melted within a DR plant, the product, direct reduced iron (DRI), still contains the gangue. For removing the gangue, the DRI has to be melted, which is typically done in an EAF, see Figure 6. The melting of DRI is often done in combination with scrap input in an EAF.

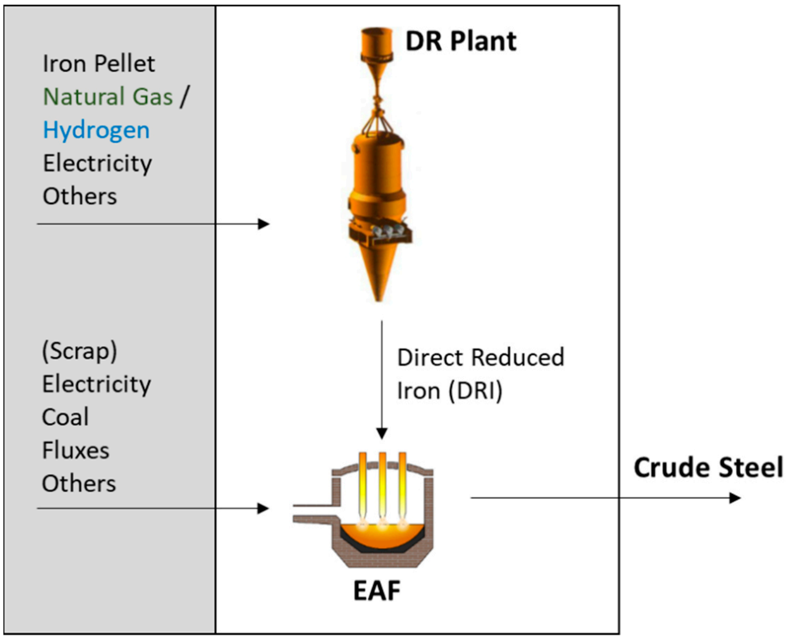

Figure 6. System boundary of crude steel production via a direct reduction plant (DR) and an electric arc furnace (EAF). Both, natural gas and hydrogen can be used as reducing agent within the DR plant.

In 2020, 106 Mio tonnes of DRI were produced globally [16]. The DR technology is fully developed and commercially available [14,72]. DR modules have reached capacities of above 2.5 Mio tonnes and thus are capable of replacing BFs on a like for like basis [14]. Therefore, DR plants provide the opportunity to enable the decarbonisation of the steel industry in time. As an intermediate solution, natural gas can be used for reducing the iron ores.

Different steel production routes towards an environmentally optimised steel production as, e.g., iron ore electrolysis, plasma direct steel production, or suspension ironmaking technology are presented by Roland Berger [73] and Agora Energiewende [72]. For most of these technologies, the low technology readiness level (TRL) is a limiting factor for a large-scale production. Thus, they do not enable a transition process in time.

In the following, (Section 5.1) the natural gas-based direct reduction and (Section 5.2) the hydrogen-based direct reduction combined with electrical melting are investigated. Special focus is given to the carbon dioxide reduction potentials and to the respective energy demand.

Most of the studies report only carbon dioxide, whereas some report GHG emissions and present the results aggregated as CO_2 equivalent. Since the steel industry processes carbon dioxide as the most significant GHG [74], the reported emissions are directly compared with each other.

5.1. Natural Gas-Based Direct Reduction with Electrical Melting

Larsson et al. (2006) delivered a comprehensive study regarding CO_2 emissions from the steel production considering the BF route and several alternative steel making processes such as the natural gas-based direct reduction with electrical melting in an EAF route (NG-

DRI/EAF route) [29]. A MIDREX® shaft furnace process is assumed for direct reduction. An exclusive scrap-based EAF operation is also considered. In addition to direct emissions from the processes, indirect emissions from raw material and energy supply are considered including emissions from transport. A strict LCA and product carbon footprint (PCF) methodology according to ISO 14040/44 and ISO 14067, respectively, is not followed, e.g., emissions from mining of coal and natural gas are not included. Credits for electricity surplus are given, but for BF slag, no credit is included in the analysis. For the electricity supply, an emission factor of 0.6 kg CO_2/kWh is assumed based on a European average power grid. The CO_2 emissions for a scrap-based EAF steel production are 0.42 kg CO_2/kg steel and for a NG-DRI/EAF steel production 1.37 kg CO_2/kg steel, see Figure 7 [29].

Barati et al. (2010) investigated the benefit of charging hot DRI with a temperature of 600 °C into an EAF compared to cold charging [75]. A GHG footprint and an energy intensity were presented. Thereby a holistic approach is followed, including the processes of mining and beneficiation of raw materials and energy sources. Used scrap shares the burden in equal parts of primarily steel production and secondarily steel production from recycling. Imported electricity is rated with a burden of 0.6 kg CO_2 eq/kWh and concerning the energy intensity for 1 kWh electricity, an energy import of 1/0.325 kWh is assumed to take a conversion efficiency into account. It is assumed that the DRI is charged together with 10% share of scrap in the EAF. For cold charging 1.45 kg CO_2/kg steel and an energy intensity of 23 MJ/kg steel is found; for hot charging 1.41 kg CO_2/kg steel and an energy intensity of 22 MJ/kg steel, see Figures 7 and 8 [75].

Within a paper by Harada and Tanka (2011), CO_2 emissions and energy requirements were presented for the use of 30% cold DRI, 80% cold DRI, 80% hot DRI in combination with scrap in an EAF as well as an exclusive scrap operation, see Figures 7 and 8 [76]. A natural gas based direct reduction via a Midrex® shaft furnace process is assumed. A holistic approach is not followed, but the focus is on direct emissions from the DR plant, the EAF, and emissions resulting from the upstream electricity supply.

Arens et al. (2017) analysed the future CO_2 emissions of the German steel industry [77]. Energy requirements and CO_2 emissions for the use of either natural gas based DRI or scrap in an EAF are investigated, see Figures 7 and 8. Indirect emissions by electricity consumption are included by assuming an emission intensity of 0.57 kg CO_2/kWh.

It was found that the electricity consumption of an EAF increases for a DRI operation by 40–120 kWh/t liquid steel compared to a scrap operation [77]. Kirschen et al. (2011) stated that the specific electrical energy demand of a typical EAF operation with DRI is about 180 kWh/t steel higher than with scrap [78]. The electric energy increases for DRI operation since the gangue has to be melted and because of the endothermic reduction reactions of the oxides. Cardenas et al. (2007) analysed this comparison of electricity demand considering several input parameters [79]. The increase of the electric energy demand for an increased DRI melting depends significantly on the DRI's grade of metallization and C-content. With an increase of 1% C in DRI, the electric energy demand decreases by 32 kWh/t steel.

Sarkar et al. (2017) has modelled a Midrex® shaft furnace and analysed the direct reduction with natural gas, syngas from coal gasification, and coke oven gas [80]. The product related energy consumption and CO_2 emissions are reported. In addition to the direct emissions from the DR plant, the upstream emissions from electric energy input into the EAF and upstream emissions from pellet import according to the WSA are included [81]. The upstream value for the pellets does not include emissions from the mining and transport of the iron ores, only from the pelletizing process. Sarkar et al. (2017) reported carbon dioxide emissions of 1.27 kg CO_2/kg steel and an energy requirement of 18.5 MJ/kg steel for a Midrex®-NG-EAF route, see Figures 7 and 8 [80].

Suer et al. (2022) presented a carbon footprint assessment of HRC produced via a natural gas and hydrogen-based DRI production with a subsequent use in an electric melting unit [74]. The DRI is put hot into the melting unit. The product of the electric melting unit is hot metal and not crude steel as it is common practice in an EAF.

Thus, the hot metal is further refined in a BOF to crude steel. The additional BOF process has, among other things, the advantage that established high grades of steel can be produced and flexible use of raw materials is possible. A product carbon footprint of 1.36 kg CO_2 eq/kg HRC according to ISO 14067 is presented, see Figure 7. An energy consumption for the processes DR plant, electric melting unit, BOF, casting, and subsequent hot-rolling is 16.2 MJ/kg HRC, see Figure 8 [74].

Within a carbon footprint assessment according to ISO 14067 of a natural gas-based DR route with an EAF, Suer et al. (2022) presented a carbon footprint of 1.36 kg CO_2 eq/kg steel, see Figure 7 [82]. A cradle-to-gate approach is followed.

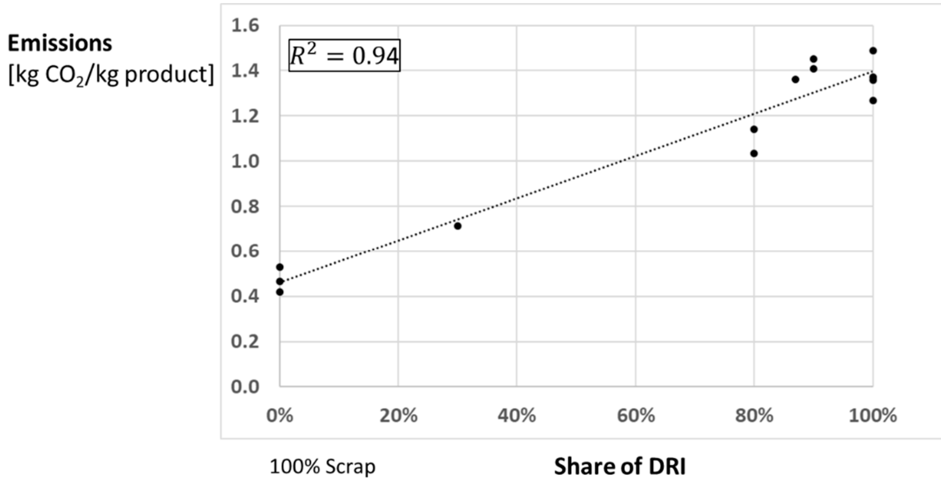

Figure 7. Carbon dioxide emissions of steel and hot-rolled coil production via a natural gas-based direct reduction (DR) plant combined with electrical melting. The emissions are presented as a function of a combined scrap and direct reduced iron (DRI) melting (kg DRI/(kg DRI + kg scrap)) [29,74–77,80,82].

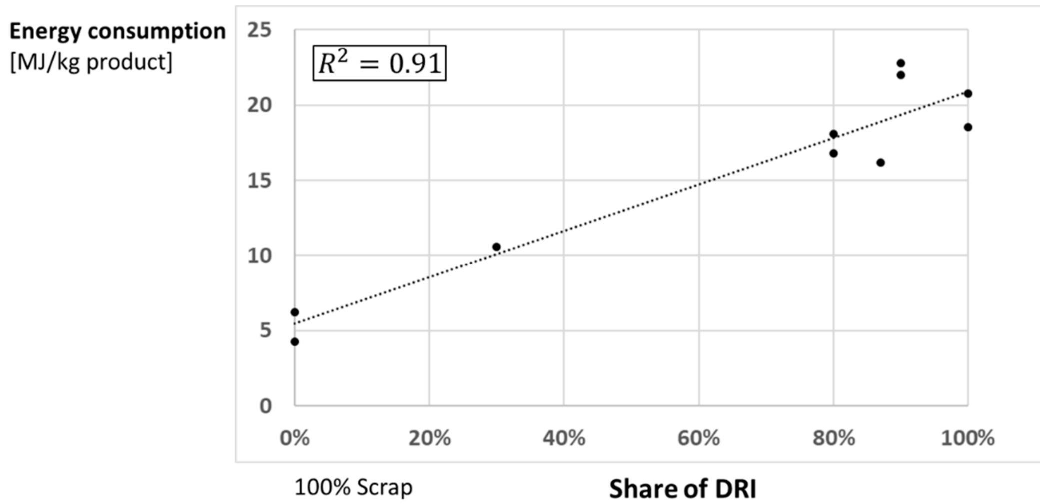

Figure 8. Energy consumption of steel and hot-rolled coil production via a natural gas-based direct reduction (DR) plant combined with electrical melting. The energy consumption is presented as a function of a combined scrap and direct reduced iron (DRI) melting (kg DRI/(kg DRI + kg scrap)) [74–77,80].

The vast number of possibilities of choosing the system boundary, making technical assumptions, and evaluating the upstream impacts of imported raw materials and energy carriers and evaluating credits for possible co-products suggests that there has to be a natural variability between the results published. In addition, there is a mix between the products steel and HRC, which are considered in the presented studies. The R-squared values, which are for both slopes above 0.91, demonstrate that the carbon dioxide emissions and the energy consumption per unit steel or HRC can be described by a linear function in dependency of the DRI/scrap ratio quite well. The results also prove that a natural gas based direct reduction plant with an electrical melting unit already has a significant potential to decarbonize the primary steel production compared to the conventional BF route. In order to further decarbonize the steel production, the natural gas for the direct reduction can be replaced by hydrogen, which shall be discussed in the next section.

5.2. Hydrogen-Based Direct Reduction with Electrical Melting

The reduction of iron ores by hydrogen is the next consequential step towards climate neutral steel production. If the hydrogen originates from water electrolysis driven by electric energy, the steel production can be based almost completely on electric energy. Thus, a shift from the present coal-based steel production towards an electricity-based metallurgy can be achieved. In the following studies, which are presented, the electric energy demand for the electrified steel production is described.

Fischedick et al. (2014) did a techno-economic evaluation of innovative steel production technologies considering the routes BF–BOF as reference, BF–BOF with carbon capture and storage (CCS), hydrogen-based direct reduction (H-DR), and iron ore electrolysis (EW) [83]. Concerning the H-DR route, the steel is produced via the Circored technology. Thereby the hydrogen is used in a fluidized bed reactor, which allows the use of fine iron ores. Subsequently, the HBI is fed into an EAF together with scrap. Fischedick et al. (2014) reported an electric energy demand of 13 MJ/kg steel for the process's electrolysis, DR plant, and EAF. Thereby the share of scrap is 0.33 kg/kg steel, see Figure 9 [83].

Otto et al. (2017) also analysed a Circored process with hydrogen as reducing agent. For a heat supply, natural gas was used. The reported total energy demand was 20 MJ/kg steel [84]. No scrap input was assumed so it is reasonable that the total energy demand was higher than the one reported by Fischedick et al. (2014) [84].

Hölling et al. (2017) analysed a direct reduction process in a shaft furnace with hydrogen as reducing agent [85]. For an electrolysis efficiency of 75% (related to higher heating value), an electric energy demand of 11.9 MJ/kg HBI is reported, where 10.8 MJ/kg HBI was required for the electrolysis process.

Vogl et al. (2018) reported an electric energy demand for the processes hydrogen electrolysis, DR plant, iron ore pellet preheating, and EAF of 12.5 MJ/kg steel when no scrap is added (Figure 9) [86]. An electrical preheating of the hydrogen is assumed and an electrolysis efficiency of 72% related to the LHV.

Bhaskar et al. (2020) modelled the steel production via the H-DR route by assessing mass and energy balances for the processes electrolyser, electrical pellet heater, electrical hydrogen heater, DRI shaft furnace, EAF, and ancillary units [87]. The DRI is charged into the EAF with a temperature of 700 °C. Special attention was given to the hydrogen's efficiency in the shaft furnace, which is described by the ratio of the actual flow rate of hydrogen to the stoichiometric flow rate of hydrogen required for the reduction reaction. This ratio was described by lambda λ. A sensitivity analysis was given concerning the energy demand as a function of lambda. For the results presented, it is assumed that lambda is equal to 1.5. No scrap input is assumed. Therefore, an electric energy demand of 13.4 MJ/kg steel is presented for the processes pellet heating, electrolyser, hydrogen heating, and EAF, see Figure 9 [87].

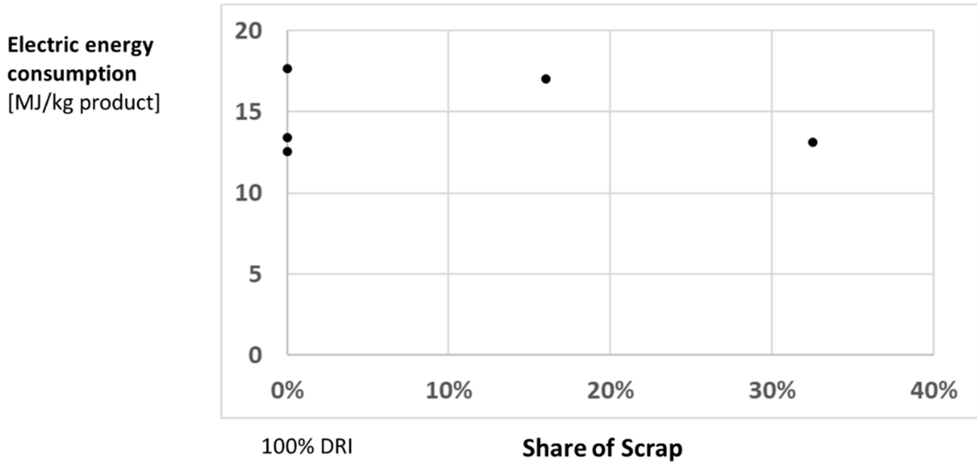

Figure 9. Electric energy consumption of steel and hot-rolled coil production via a hydrogen-based direct reduction (DR) plant combined with electrical melting. The energy consumption is presented as function of a combined scrap and direct reduced iron (DRI) melting (kg scrap/kg product) [74,82,83,86,87].

Suer et al. [74] analysed a hydrogen-based DR plant with an integrated electric melting unit. The hydrogen is produced by water electrolysis powered by electric energy with an efficiency of 62.5% related to the LHV. The preheating of the hydrogen for the DR plant is electrified. The DRI is charged hot into the electric melting unit. The hot medal, the product of the melting unit, is further refined in a BOF to crude steel and further refined to steel and HRC. An electric energy demand for the process's electrolyser, DR plant, electric melting unit, BOF, casting, and hot rolling of 17 MJ/kg HRC is presented, see Figure 9 [74].

Within a carbon footprint assessment of a H-DR route with an EAF, Suer et al. (2022) [82] presented an electric energy demand of 17.6 MJ/kg steel, see Figure 9. An equation is given for the carbon footprint calculation of the steel as a function of the carbon footprint of the electricity's grid mix following a holistic approach according to ISO 14067.

The results presented do not give a clear statement concerning the electric energy demand for a hydrogen-based DR route. Yet, this is expectable regarding the number of assumptions which have to be made: chosen system boundary, choice of product (steel, HRC), efficiency of electrolysis process, efficiency of hydrogen as reducing agent (lambda), charging temperature of the DRI in the electrical melter, choice of DR process (shaft furnace, fluidized bed reactor etc.), existence of pellet preheating, iron ore qualities, use of lime carbonates, or burnt quicklime in the EAF, amongst others.

Concerning the carbon dioxide emissions, the DR plant can be completely based on hydrogen so that no emissions are emerged directly from the DR plant. Concerning the EAF process a range between 0.053 kg CO_2/kg steel [86] and 0.18 kg CO_2/kg steel [83] are reported. These result from the use of coal and limestone and from the consumption of the electrodes in an EAF [86]. Carbon is required in order to produce a foaming slag, which infolds the electrodes and thus reduces radiation losses and protects the refractories [43]. Thus, the steel industry will still require metallurgical carbon leading to CO_2 emissions. However, in comparison with the BF route, which causes about 2.0 kg CO_2/kg steel, the combination of a DR plant with an electric melting unit or an EAF represents a significant improvement.

In a carbon footprint assessment, a GWP of 0.76 kg CO_2 eq/kg HRC is reported for a hydrogen-based steel production if the hydrogen and electric energy input is completely from renewable energies [74]. For a hydrogen-based steel production with an electric energy mix of a European sustainable scenario for the year 2040, a carbon footprint of 0.75 kg CO_2 eq/kg steel is reported by Suer et al. (2022) [82]. Thereby the raw material inputs are evaluated with data from 2018 to 2021, so no incremental improvements were considered.

Since it is possible for the steel production to completely be shifted from coal to electricity, the way of producing the electricity is absolutely crucial.

6. Conclusions

The actual discussion about a common 'green steel' definition raises the problem of an adequate allocation of environmental burdens between primary and secondary steel production. Therefore, a literature review spanning more than the last 20 years is presented in which LCA recycling methodologies for steel and metals are intensively discussed. Within numerous papers, it is pointed out that for metals with a limited supply of recycled feedstock, external market stimulation is ineffective and may result in inefficient processing and unnecessary transportation. In addition, the increasing steel demand cannot be filled by scrap recycling alone even until the year 2050 and beyond. If a 'green steel' definition does not follow a global perspective but only the emissions of a specific steel producer, it might be easier for steel producers to shift partially from primary to secondary steel production than implementing breakthrough technologies within the primary route. Thus, a global environmental improvement cannot be achieved.

Life cycle assessments for steel are presented for the currently most dominant blast furnace route and for the scrap recycling electric arc furnace (EAF) route. Whereas the literature availability of LCAs for the blast furnace related steel production route is high, there is a lack of LCAs for the EAF related steel production route. Differences in LCA results between the studies are analysed in a novel detailed perspective. Concerning the methodology differences, important aspects are the evaluation of the scrap recycling potential and the evaluation of co-products. Referring to the technological differences, the quality of the feedstock, and the amount of scrap used, all have a significant impact on the results. For the scrap recycling route, especially the electricity mix used for the EAF, has significant importance.

Since breakthrough technologies within the primary route are required, modifications for the blast furnace route are presented as a first step. By injecting hydrogen into existing blast furnaces, greenhouse gas (GHG) emissions can be reduced and a market for hydrogen can be established. Besides the injection of hydrogen, the use of pre-reduced iron ores in a blast furnace is investigated. Within a novel approach, data from metallurgical modelling and data from technical field tests are combined with LCAs for hydrogen production.

Since coke is required in a blast furnace for gas permeability in the shaft furnace and as supporting matrix, the steel production via a blast furnace cannot be completely decarbonized. Direct reduction (DR) plants are technically mature and capable to support a transition away from coal and towards natural gas and ultimately hydrogen. Both a natural gas-based and a hydrogen-based direct reduction were analysed. The DRI is further electrically melted in combination with scrap. The GHG emissions and the energy demand per unit steel are presented as function of the DRI/scrap ratio. The future electric energy demand, which is required for hydrogen electrolysis and directly for the steel production processes, is presented. The results give decision makers from politics and the steel industry guidance on how much renewable electric energy is required in order to decarbonize the steel industry. In the future, LCAs from primary data for these scenarios would be important to highlight the influence of the steel transformation on other impact categories. Within a social life cycle assessment, social impacts should also be investigated.

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References

1. IPCC. Climate Change 2021: The Physical Science Basis. In *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., et al., Eds.; Cambridge University Press: Cambridge, UK, 2021.
2. IEA (International Energy Agency). Iron and Steel Technology Roadmap—Towards More Sustainable Steelmaking. 2020, pp. 38–43. Available online: https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf (accessed on 26 January 2022).
3. Wang, P.; Ryberg, M.; Yang, Y.; Feng, K.; Kara, S.; Hauschild, M.; Chen, W.-Q. Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. *Nat. Commun.* **2021**, *12*, 2066. [CrossRef] [PubMed]
4. Nidheesh, P.V.; Kumar, M.S. An overview of environmental sustainability in cement and steel production. *J. Clean. Prod.* **2019**, *231*, 856–871. [CrossRef]
5. Hasanbeigi, A.; Arens, M.; Price, L. Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction: A technical review. *Renew. Sustain. Energy Rev.* **2014**, *33*, 645–658. [CrossRef]
6. Ariyama, T.; Takahashi, K.; Kawashiri, Y.; Nouchi, T. Diversification of the Ironmaking Process Toward the Long-Term Global Goal for Carbon Dioxide Mitigation. *J. Sustain. Met.* **2019**, *5*, 276–294. [CrossRef]
7. Pardo, N.; Moya, J.A. Prospective scenarios on energy efficiency and CO_2 emissions in the European Iron & Steel industry. *Energy* **2013**, *54*, 113–128. [CrossRef]
8. *ISO 14040*; DIN EN ISO 14040:2006 + Amd 1:2020. Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
9. *ISO 14044*; DIN EN ISO 14044:2006 + Amd 1:2017 + Amd 2:2020. Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
10. Liang, T.; Wang, S.; Lu, C.; Jiang, N.; Long, W.; Zhang, M.; Zhang, R. Environmental impact evaluation of an iron and steel plant in China: Normalized data and direct/indirect contribution. *J. Clean. Prod.* **2020**, *264*, 121697. [CrossRef]
11. Olmez, G.M.; Dilek, F.B.; Karanfil, T.; Yetis, U. The environmental impacts of iron and steel industry: A life cycle assessment study. *J. Clean. Prod.* **2016**, *130*, 195–201. [CrossRef]
12. Koltun, P.; Klymenko, V. Cradle-to-gate life cycle assessment of the production of separated mix of rare earth oxides based on Australian production route. *Min. Miner. Deposits* **2020**, *14*, 1–15. [CrossRef]
13. Tönjes, A.; Lechtenböhmer, S.; Leipprand, A.; Zelt, O. Klimaneutraler Stahl Made in Germany: Transformationsherausforderungen im Kontext steigender Marktanforderungen. 2022. Available online: https://epub.wupperinst.org/frontdoor/deliver/index/docId/7924/file/7924_Toenjes.pdf (accessed on 10 October 2022).
14. Liu, W.; Zuo, H.; Wang, J.; Xue, Q.; Ren, B.; Yang, F. The production and application of hydrogen in steel industry. *Int. J. Hydrogen Energy* **2021**, *46*, 10548–10569. [CrossRef]
15. Wang, R.; Zhao, Y.; Babich, A.; Senk, D.; Fan, X. Hydrogen direct reduction (H-DR) in steel industry—An overview of challenges and opportunities. *J. Clean. Prod.* **2021**, *329*, 129797. [CrossRef]
16. WSA. World Steel Association: World Steel in Figures. 2021. Available online: https://worldsteel.org/wp-content/uploads/2021-World-Steel-in-Figures.pdf (accessed on 26 January 2022).
17. WSA. *World Steel Association: Life Cycle Assessment Methodology Report*; World Steel Association: Brussels, Belgium, 2011.
18. WSA. *World Steel Association: World Steel Life Cycle Inventory Methodology Report*; World Steel Association: Brussels, Belgium, 2000.
19. Atherton, J. Declaration by the Metals Industry on Recycling Principles. *Int. J. Life Cycle Assess.* **2007**, *12*, 59–60. [CrossRef]
20. Birat, J.-P.; Prum, N.; Yonezawa, K.; Aboussouan, L. The value of recycling to society and its internalization into LCA methodology. *Rev. Met.* **2006**, *103*, 50–61. [CrossRef]
21. Neugebauer, S.; Finkbeiner, M. *Ökobilanz nach ISO 14040/44 für das Multirecycling von Stahl*; Wirtschaftsvereinigung Stahl: Düsseldorf, Germany, 2012.
22. Finkbeiner, M.; Bach, V.; Lehmann, A. *Environmental Footprint. der Umweltfußabdruck von Produkten und Dienstleistungen—Abschlussbericht*; On behalf of German Federal Environment Agency; Umweltbundesamt: Dessau-Roßlau, Germany, 2018; ISSN 1862-4804.
23. European Union (EU). Product Environmental Footprint Category Rules (PEFCR) for Metal Sheets for Various Applications. 2019. Available online: https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm (accessed on 26 January 2022).
24. Frischknecht, R. LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency. *Int. J. Life Cycle Assess.* **2010**, *15*, 666–671. [CrossRef]
25. Yellishetty, M.; Mudd, G.M.; Ranjith, P.; Tharumarajah, A. Environmental life-cycle comparisons of steel production and recycling: Sustainability issues, problems and prospects. *Environ. Sci. Policy* **2011**, *14*, 650–663. [CrossRef]
26. Reale, F.; Buttol, P.; Cortesi, S.; Mengarelli, M.; Masoni, P.; Scalbi, S.; Zamagni, A. Dealing with LCA Modeling for the end of life of mechatronic products. *Environ. Eng. Manag. J.* **2015**, *14*, 1691–1704. [CrossRef]

27. Mengarelli, M.; Neugebauer, S.; Finkbeiner, M.; Germani, M.; Buttol, P.; Reale, F. End-of-life modelling in life cycle assessment—Material or product-centred perspective? *Int. J. Life Cycle Assess.* **2016**, *22*, 1288–1301. [CrossRef]
28. Volkhausen, W. Methodische Beschreibung und Bewertung der umweltgerechten Gestaltung von Stahlwerkstoffen und Stahlerzeugnissen. 2003. Available online: https://nbn-resolving.org/urn:nbn:de:swb:105-0625177 (accessed on 28 October 2022).
29. Larsson, M.; Grip, C.-E.; Ohlsson, H.; Rutqvist, S.; Wikström, J.-O.; Ångström, S. Comprehensive Study Regarding Greenhouse Gas Emission from Iron Ore Based Production at the Integrated Steel Plant SSAB Tunnplåt AB. *Int. J. Green Energy* **2006**, *3*, 171–183. [CrossRef]
30. Guidehouse. Gas Decarbonisation Pathways 2020–2050. Gas for Climate. 2020. Available online: https://gasforclimate2050.eu/wp-content/uploads/2020/04/Gas-for-Climate-Gas-Decarbonisation-Pathways-2020-2050.pdf (accessed on 28 October 2022).
31. Agora. No-Regret Hydrogen. Charting Early Steps for H2 Infrastructure in Europe. 2021. Available online: https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_02_EU_H2Grid/A-EW_203_No-regret-hydrogen_WEB.pdf (accessed on 1 June 2022).
32. Norgate, T.E.; Jahanshahi, S.; Rankin, W.J. Assessing the environmental impact of metal production processes. *J. Clean. Prod.* **2007**, *15*, 838–848. [CrossRef]
33. Burchart-Korol, D. Life cycle assessment of steel production in Poland: A case study. *J. Clean. Prod.* **2013**, *54*, 235–243. [CrossRef]
34. Renzulli, P.A.; Notarnicola, B.; Tassielli, G.; Arcese, G.; Di Capua, R. Life Cycle Assessment of Steel Produced in an Italian Integrated Steel Mill. *Sustainability* **2016**, *8*, 719. [CrossRef]
35. *DIN EN 19694-2*; Stationary Source Emissions—Greenhouse Gas (GHG) Emissions in Energy-Intensive Industries—Part 2: Iron and Steel Industry. Deutsches Institut für Normung: Berlin, Germany, 2016.
36. Chisalita, D.-A.; Petrescu, L.; Cobden, P.; van Dijk, H.; Cormos, A.-M.; Cormos, C.-C. Assessing the environmental impact of an integrated steel mill with post-combustion CO_2 capture and storage using the LCA methodology. *J. Clean. Prod.* **2019**, *211*, 1015–1025. [CrossRef]
37. IEA (International Energy Agency). Iron and Steel CCS Study. (Techno-Economis Integrated Steel Mill). 2013. Available online: https://ieaghg.org/docs/General_Docs/Reports/2013-19.pdf (accessed on 26 January 2022).
38. Backes, J.; Suer, J.; Pauliks, N.; Neugebauer, S.; Traverso, M. Life Cycle Assessment of an Integrated Steel Mill Using Primary Manufacturing Data: Actual Environmental Profile. *Sustainability* **2021**, *13*, 3443. [CrossRef]
39. Bach, V.; Finkbeiner, M. Approach to qualify decision support maturity of new versus established impact assessment methods—Demonstrated for the categories acidification and eutrophication. *Int. J. Life Cycle Assess.* **2017**, *22*, 387–397. [CrossRef]
40. Khalid, Y.; Wu, M.; Silaen, A.; Martinez, F.; Okosun, T.; Worl, B.; Low, J.; Zhou, C.; Johnson, K.; White, D. Oxygen enrichment combustion to reduce fossil energy consumption and emissions in hot rolling steel production. *J. Clean. Prod.* **2021**, *320*, 128714. [CrossRef]
41. Schmitz, N.; Sankowski, L.; Kaiser, F.; Schwotzer, C.; Echterhof, T.; Pfeifer, H. Towards CO_2-neutral process heat generation for continuous reheating furnaces in steel hot rolling mills—A case study. *Energy* **2021**, *224*, 120155. [CrossRef]
42. Dutta, S.K.; Chokshi, Y.B. *Basic Concepts of Iron and Steel Making*; Springer: Berlin/Heidelberg, Germany, 2020. [CrossRef]
43. MacRosty, R.D.M.; Swartz, C.L.E. Dynamic optimization of electric arc furnace operation. *AIChE J.* **2007**, *53*, 640–653. [CrossRef]
44. Babich, A. Blast furnace injection for minimizing the coke rate and CO_2 emissions. *Ironmak. Steelmak.* **2021**, *48*, 728–741. [CrossRef]
45. Remus, R.; Aguado-Monsonet, M.; Roudier, S.; Sancho, L.D. *Best Available Techniques (BAT) Reference Document for Iron and Steel Production: Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control). (No. JRC69967)*; Joint Research Centre (Seville Site): Seville, Spain, 2013. [CrossRef]
46. Lüngen, H.B.; Schmöle, P. Comparison of Blast Furnace Operation Modes in the World. *Steel Res. Int.* **2020**, *91*, 2000182. [CrossRef]
47. Gudenau, H.W.; Gebel, U.; Gerlach, W.; Grandin, F.H.; Guntermann, K.; Hoberg, H.; Kim, S.; Koerfer, M.; Mulanza, J.P.; Pintsch, S.; et al. *Eisenhüttenmännische Verfahrenstechnik. Vom Erz zum Stahl*; Druck-& Verlagshaus MAINZ GmbH: Aachen, Germany, 1989.
48. Thyssenkrupp Steel Europe AG. Wasserstoff Statt Kohle. 2019. Available online: https://www.thyssenkrupp-steel.com/de/newsroom/pressemitteilungen/wasserstoff-statt-kohle.html (accessed on 26 January 2022).
49. Spreitzer, D.; Schenk, J. Reduction of Iron Oxides with Hydrogen—A Review. *Steel Res. Int.* **2019**, *90*, 1900108. [CrossRef]
50. Nogami, H.; Kashiwaya, Y.; Yamada, D. Simulation of Blast Furnace Operation with Intensive Hydrogen Injection. *ISIJ Int.* **2012**, *52*, 1523–1527. [CrossRef]
51. Bernasowski, M. Theoretical Study of the Hydrogen Influence on Iron Oxides Reduction at the Blast Furnace Process. *Steel Res. Int.* **2014**, *85*, 670–678. [CrossRef]
52. Yilmaz, C.; Wendelstorf, J.; Turek, T. Modeling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions. *J. Clean. Prod.* **2017**, *154*, 488–501. [CrossRef]
53. Schmöle, P. The blast furnace—Fit for the future? *Stahl und Eisen* **2016**, *136*, 31–40.
54. de Castro, J.A.; Takano, C.; Yagi, J.-I. A theoretical study using the multiphase numerical simulation technique for effective use of H 2 as blast furnaces fuel. *J. Mater. Res. Technol.* **2017**, *6*, 258–270. [CrossRef]
55. Mehmeti, A.; Angelis-Dimakis, A.; Arampatzis, G.; McPhail, S.J.; Ulgiati, S. Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies. *Environments* **2018**, *5*, 24. [CrossRef]
56. Jampani, M.; Gibson, J.; Pistorius, P.C. Increased Use of Natural Gas in Blast Furnace Ironmaking: Mass and Energy Balance Calculations. *Met. Mater. Trans. A* **2019**, *50*, 1290–1299. [CrossRef]

57. De Castro, J.A.; Nogami, H.; Yagi, J.-I. Numerical Investigation of Simultaneous Injection of Pulverized Coal and Natural Gas with Oxygen Enrichment to the Blast Furnace. *ISIJ Int.* **2002**, *42*, 1203–1211. [CrossRef]
58. Nogami, H.; Yagi, J.-I.; Kitamura, S.-Y.; Austin, P.R. Analysis on Material and Energy Balances of Ironmaking Systems on Blast Furnace Operations with Metallic Charging, Top Gas Recycling and Natural Gas Injection. *ISIJ Int.* **2006**, *46*, 1759–1766. [CrossRef]
59. Efetürk, M.; Janz, A.; Sprecher, M.; Peter, R.; Hölsken, T. Verwendung von Koksofengas als Reduktionsmittel im Hochofenprozess. *Stahl + Technik 2*. 2020. Available online: https://www.stahl-und-technik.de/artikel/verwendung-von-koksofengas-als-reduktionsmittel-im-hochofenprozess (accessed on 28 September 2022).
60. Suopajärvi, H.; Umeki, K.; Mousa, E.; Hedayati, A.; Romar, H.; Kemppainen, A.; Wang, C.; Phounglamcheik, A.; Tuomikoski, S.; Norberg, N.; et al. Use of biomass in integrated steelmaking—Status quo, future needs and comparison to other low-CO_2 steel production technologies. *Appl. Energy* **2018**, *213*, 384–407. [CrossRef]
61. Asanuma, M.; Ariyama, T.; Sato, M.; Murai, R.; Nonaka, T.; Okochi, I.; Tsukiji, H.; Nemoto, K. Development of Waste Plastics Injection Process in Blast Furnace. *ISIJ Int.* **2000**, *40*, 244–251. [CrossRef]
62. Babich, A.; Senk, D.; Knepper, M.; Benkert, S. Conversion of injected waste plastics in blast furnace. *Ironmak. Steelmak.* **2016**, *43*, 11–21. [CrossRef]
63. Duarte, P.; Becerra, J.; Scarnati, T. ENERGIRON direct reduction technology—Economical, flexible, environmentally friendly. *Acero LatinoAmericano* **2008**, *6*, 52–58.
64. Martinez, J.; Duarte, P. *Tenova HYL NEWS*; Tenova HYL (HYL Technologies, S.A. de C.V.): Monterrey, Mexico, 2017.
65. Schmöle, P.; Lüngen, H.B. Use of pre-reduced material in the blast furnace: Metallurgical, ecological and economic aspects. *In Stahl und Eisen* **2007**, *127*, 47–54.
66. Yilmaz, C.; Turek, T. Modeling and simulation of the use of direct reduced iron in a blast furnace to reduce carbon dioxide emissions. *J. Clean. Prod.* **2017**, *164*, 1519–1530. [CrossRef]
67. Dutta, S.K.; Sah, R. Direct Reduced Iron: Production. In *Encyclopedia of Iron, Steel, and Their Alloys*; Taylor and Francis: New York, NY, USA, 2016; pp. 1082–1108. [CrossRef]
68. Müller, N.; Herz, G.; Reichelt, E.; Jahn, M. CO_2 Emission Reduction Potential in the Steel Industry by Integration of a Direct Reduction Process into Existing Steel Mills (No. DGMK–2018-2). 2018. Available online: https://inis.iaea.org/collection/NCLCollectionStore/_Public/49/107/49107596.pdf?r=1 (accessed on 29 January 2022).
69. Griesser, A.; Buergler, T. Use of HBI in Blast Furnace. *BHM Berg- und Hüttenmännische Monatshefte* **2019**, *164*, 267–273. [CrossRef]
70. Kobe Steel. KOBELCO Group's CO_2 Reduction Solution for Blast Furnace Ironmaking. 16 February 2021. Available online: https://www.kobelco.co.jp/english/releases/files/20210216_e.pdf (accessed on 29 January 2022).
71. Suer, J.; Traverso, M.; Ahrenhold, F. Carbon footprint of scenarios towards climate-neutral steel according to ISO 14067. *J. Clean. Prod.* **2021**, *318*, 128588. [CrossRef]
72. Agora Energiewende. Klimaneutrale Industrie. Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement. Berlin, November 2019. Available online: https://www.agora-energiewende.de/veroeffentlichungen/klimaneutrale-industrie-hauptstudie/ (accessed on 8 March 2022).
73. Berger, R. *The Future of Steelmaking. How the European Steel Industry Can Achieve Carbon Neutrality*; Roland Berger GMBH: Munich, Germany, 2020.
74. Suer, J.; Ahrenhold, F.; Traverso, M. Carbon Footprint and Energy Transformation Analysis of Steel Produced via a Direct Reduction Plant with an Integrated Electric Melting Unit. *J. Sustain. Met.* **2022**, 1–14. [CrossRef]
75. Barati, M. Energy intensity and greenhouse gases footprint of metallurgical processes: A continuous steelmaking case study. *Energy* **2010**, *35*, 3731–3737. [CrossRef]
76. Harada, T.; Tanaka, H. Future Steelmaking Model by Direct Reduction Technologies. *ISIJ Int.* **2011**, *51*, 1301–1307. [CrossRef]
77. Arens, M.; Worrell, E.; Eichhammer, W.; Hasanbeigi, A.; Zhang, Q. Pathways to a low-carbon iron and steel industry in the medium-term—The case of Germany. *J. Clean. Prod.* **2017**, *163*, 84–98. [CrossRef]
78. Kirschen, M.; Badr, K.; Pfeifer, H. Influence of direct reduced iron on the energy balance of the electric arc furnace in steel industry. *Energy* **2011**, *36*, 6146–6155. [CrossRef]
79. Cardenas, J.G.G.; Conejo, A.N.; Gnechi, G.G. Optimization of energy consumption in electric arc furnaces operated with 100% DRI. *Metal* **2007**, *2017*, 1–7.
80. Sarkar, S.; Bhattacharya, R.; Roy, G.G.; Sen, P.K. Modeling MIDREX Based Process Configurations for Energy and Emission Analysis. *Steel Res. Int.* **2017**, *89*, 1700248. [CrossRef]
81. WSA. *World Steel Association: CO_2 Data Collection. User Guide, Version 10*; World Steel Association: Brussels, Belgium, 2021.
82. Suer, J.; Jäger, N.; Traverso, M. Carbon footprint assessment of hydrogen and related hydrogen-based steel production. 2022. *in press*.
83. Fischedick, M.; Marzinkowski, J.; Winzer, P.; Weigel, M. Techno-economic evaluation of innovative steel production technologies. *J. Clean. Prod.* **2014**, *84*, 563–580. [CrossRef]
84. Otto, A.; Robinius, M.; Grube, T.; Schiebahn, S.; Praktiknjo, A.; Stolten, D. Power-to-Steel: Reducing CO_2 through the Integration of Renewable Energy and Hydrogen into the German Steel Industry. *Energies* **2017**, *10*, 451. [CrossRef]
85. Hölling, M.; Weng, M.; Gellert, S. Bewertung der Herstellung von Eisenschwamm unter Verwendung von Wasserstoff. *Stahl Und Eisen* **2017**, *137*, 47–53.

86. Vogl, V.; Åhman, M.; Nilsson, L.J. Assessment of hydrogen direct reduction for fossil-free steelmaking. *J. Clean. Prod.* **2018**, *203*, 736–745. [CrossRef]
87. Bhaskar, A.; Assadi, M.; Somehsaraei, H.N. Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen. *Energies* **2020**, *13*, 758. [CrossRef]

2.2 Carbon footprint of scenarios towards climate-neutral steel production

This section presents publication II 'Suer, J., Traverso, M., Ahrenhold, F.: Carbon footprint of scenarios towards climate-neutral steel according to ISO 14067. *Journal of Cleaner Production* (2021). https://10.1016/j.jclepro.2021.128588.' In this study a PCF is presented for a BF-based steel produced at an integrated steel site at the example of thyssenkrupp Steel Europe AG in 2018. Another PCF is presented for four intermediate scenarios:

- Injection of NG in a BF
- Injection of H_2 in a BF
- Use of NG-based HBI In a BF
- Use of H_2-based HBI in a BF

The PCF of the conventional steel serves as a baseline. This baseline is enhanced by integrating metallurgical models, from literature, for the considered scenarios. Thus, these scenarios are assessed in a holistic approach, in which all changes of the complex material and energy supply chain are reported. In a sensitivity analysis a comparison is given for the use of hydrogen in a BF to that in a DR plant. This comparison helps steel producers to maximize the efficiency of hydrogen use.

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Carbon footprint of scenarios towards climate-neutral steel according to ISO 14067

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ABSTRACT

Within this paper, new findings of the potential of four considered intermediate solutions towards a primary climate-neutral steel production are reported. (1) Injection of natural gas into a blast furnace, (2) injection of hydrogen into a blast furnace, (3) natural gas-based direct reduction with subsequent input of the hot briquetted iron (HBI) in a blast furnace, and (4) hydrogen-based direct reduction with subsequent input of the hot briquetted iron in a blast furnace.

The current study is a carbon footprint assessment applied to the product hot-rolled coil (HRC) according to the ISO norm 14067:2019. A *cradle to gate* approach is used including the production of raw materials to the production of hot-rolled coil. To define a reference point, a carbon footprint of hot-rolled coil produced via a typical blast furnace – basic oxygen furnace (BF-BOF) route is presented. The basic data set is based on primary data from the integrated site of *thyssenkrupp Steel Europe AG (tkSE)*, year 2018. Within a novel approach, this base line is enhanced by integrating metallurgical models from the literature. Thereby all changes of the complex material and energy supply chain of an integrated site and of the upstream chain are reported. The carbon footprint of each process unit is presented in detail so that optimization potentials are identified, which impacts are analysed within a sensitivity analysis. A holistic comparison of using hydrogen in a blast furnace to using hydrogen in a direct reduction plant is presented and delivers important findings. This can help steel producers to maximize the efficiency of hydrogen use.

Since the focus of this paper lies on the comparison of steel production routes and the assessments for all considered scenarios are based on the same methodologies and databases the sensitivity of made assumptions on the deltas between these scenarios is much weakened than the sensitivity of absolute values. That's one of the reasons why, the conclusions of this paper, which are referred to the plant of tkSE, can be transferred to other production sites, as well. The presented results can help decision-makers to know the potentials of possible intermediate solutions towards a climate-neutral steel production and how the potentials can be maximized.

The carbon footprint of the product hot-rolled coil is 2.1 t CO_2eq/t_{HRC} following the *recycled content* approach and 0.82 t CO_2eq/t_{HRC} following the *end-of-life recycling* approach. The reduction potential for the carbon footprint is about 4 % for injecting natural gas into a blast furnace and about 9 % for injecting hydrogen into a blast furnace. The hydrogen is produced via electrolysis driven by a renewable German energy mix, year 2018. Using hot briquetted iron (HBI) within a blast furnace leads to a reduction potential between 5 % and 12 % for natural gas based-HBI and between 10 % and 17 % for H_2-based HBI. The reduction potential strongly depends on the iron feedstock, which is replaced by the hot briquetted iron. Between 4.5 and 7.0 kg CO_2eq/kg H_2 are avoided by injecting hydrogen into a blast furnace, and about 5.4 kg CO_2eq/kg H_2 are prevented if the hydrogen is injected into a direct reduction plant.

1. Introduction

According to the Paris Agreement of 2015 to keep the global warming below 2 °C, the European Council aims to reduce greenhouse gas (GHG) emissions by about 40 % by 2030 and 80–95 % by 2050, compared to 1990 levels (EU, 2016). The energy-intensive steel industry is a large emitter of GHG emissions accounting about 7 % of total world CO_2 emissions (IEA, 2020). Steel is produced primarily from natural raw

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materials or secondarily from scrap use. The primary blast furnace (BF) – basic oxygen furnace (BOF) route and the secondary scrap-based electric arc furnace (EAF) route are the most dominant steel production routes. According to the World Steel Association (2020), the share of BF-BOF route is globally about 72 % and of EAF route 28 % in the year 2019. The BF-BOF route's average primary energy is about 23 GJ per tonnes of crude steel (CS) and for scrap-based EAF route about 5.2 GJ/t_{CS} (IEA, 2020). The direct and indirect carbon dioxide emissions for the BF-BOF route are about 2.2 t CO_2/t_{CS} and about 0.3 t CO_2/t_{CS} for the scrap-based EAF route (IEA, 2020). However, at least until 2050, the availability of scrap is limited and only 44 % of the steel demand can be covered by the EAF route (Wörtler et al., 2013). For reaching the declared goals of the EU, breakthrough technologies within the primary route are required (Pardo and Moya, 2013).

According to a recent scenario analysis (Roland Berger, 2020) the most promising technology towards carbon-neutral steel production is the route H_2-based direct reduction of iron ore with subsequently smelting of the direct reduced iron (DRI) in an electric arc furnace (H-DR route). Furthermore, even when taking natural gas as reductant for DRI production, the overall GHG emissions are significantly lower than producing over the BF-BOF route taking coal and coke as reductants (IEA, 2020). Fischedick et al. (2014) give a techno-economic evaluation of the BF-BOF route as a basis compared to the innovative scenarios BF with carbon capture and storage (CCS), H-DR, and iron ore electrolysis (EW). The development of the prices for renewable energy as well as for CO_2 allowances determine when the routes H-DR and EW become economically attractive (Fischedick et al., 2014). The most significant energy demand for H-DR route is for the electrolyser of hydrogen production. However, even if the importance of using hydrogen as reductant in the steel manufacturing is already identified as a relevant action to reduce the GHG emissions of steel production (Roland Berger, 2020; Fischedick et al., 2014; Vogl et al., 2018; Bhaskar et al., 2020; Hölling et al., 2017), some technological and structural barriers must be overcome.

In the year 2019, only 0.7 million tons of direct reduced iron were produced in Europe whereas about 94 million tons of crude steel were produced via BF-BOF route (WSA, 2020c). As a result, the possible demand for hydrogen for the direct reduction based route (H-DR) is presently limited in Europe. By using hydrogen on an interim basis in existing blast furnaces a demand can be generated quickly so that supply can follow. Within the BF-BOF route the blast furnace accounts for the highest share of emissions, having an impact of about 1.5 t CO_2 per tonnes of hot metal (HM). These emissions result from the fact that about 420 kg/t_{HM} of carbon input is necessary for the reduction and melting of the iron ore (DIN EN, 19694–2, 2016). The chance of firstly, making a first move for establishing a hydrogen infrastructure, and secondly, reducing GHG emissions of the most significant driver within the currently most dominant BF-BOF route, leads to the first scenario of this paper: A carbon footprint assessment of using hydrogen as reducing agent into a blast furnace. Nevertheless, as long as the supply of hydrogen is limited the replacement of coal by natural gas into a blast furnace is another possible option to reduce the carbon input into a blast furnace so this scenario is part of this work as well.

Another interim technology to pave the way towards the H-DR route is the use of hot briquetted iron (HBI) in an existing blast furnace (Martinez and Duarte, 2017). Thus, the blast furnace functions more a melting than as a reducing unit (Schmöle, 2016). The blast furnace efficiency increases and its GHG emissions reduce (Martinez and Duarte, 2017). The following presented scientific literature describes these scenarios concerning direct carbon dioxide emissions.

In a traditional blast furnace (BF) coke and pulverized coal injection (PCI) serve as reduction agents and energy suppliers. For a complete replacement of pulverized coal (PC), Schmöle (2016) reported an injection of 100 kg/t_{HM} of natural gas, and an increasing amount of 367 kg/t_{HM} of coke. This operation mode results in a reduction of 106 kg CO_2/t_{HM}.

As another possibility for full substitution of pulverized coal, Schmöle (2016) investigated the injection of 40 kg H_2/t_{HM}, which resulted in a coke rate of 392 kg/t_{HM}. By this operation mode, a reduction of 292 kg CO_2/t_{HM} was predicted by Schmöle (2016). Yilmaz et al. (2017) investigated the injection of hydrogen into a blast furnace as well. For a full replacement of pulverized coal, they reported an injection of 27.5 kg H_2/t_{HM}, which resulted in a coke rate of 390 kg/t_{HM} and a reduction of 289 kg CO_2/t_{HM}. The amount of required coke and the carbon dioxide reduction for a full replacement of pulverized coal is very close to Schmöle's results (2016). Yet, whereas Schmöle (2016) reported an injection of 40 kg H_2/t_{HM}, Yilmaz et al. (2017) named 27.5 kg H_2/t_{HM}. This difference can be explained by the fact that Yilmaz et al. (2017) assumed an injection temperature of 1200 °C for the hydrogen, whereas Schmöle (2016) did not assume a preheating of the hydrogen.

Beyond replacing carbon with hydrogen, emissions of a BF are reduced when inserting pre-reduced pellets instead of iron oxides. For the use of 400 kg HBI/t_{HM}, Schmöle (2016) reported an emission reduction of 377 kg CO_2/t_{HM}. Yilmaz and Turek (2017) examined that for the use of 400 kg/t_{HM} of HBI into a BF the CO_2 emissions of the BF are cut down on 361 kg CO_2/t_{HM} in comparison with the reference BF-route. This result is consistent with the result of Schmöle (2016).

The carbon dioxide emissions of the blast furnace decrease linearly with an increasing amount of HBI until about 400 kg/t_{HM} (Yilmaz and Turek, 2017). Yilmaz and Turek (2017) included the emissions from the direct reduction plant (DRP) into the system boundaries, considering both, injection of hydrogen and natural gas into the DRP. For natural gas (NG)-based DRI the emissions of the DRP are between 410 and 500 kg CO_2/t_{DRI} and when using hydrogen, the emissions are nearly zero. In addition, they analysed the influence of the carbon content in the HBI on the potential of emission reduction. The specific carbon dioxide reduction per input HBI into a blast furnace is in summary more efficient for a higher C content in the HBI, considering that the bonded carbon is needed inside the blast furnace anyway. Martinez and Duarte (2017) reported that up to 35 % energy of hydrogen (lower heating value) combined with 65 % energy of natural gas input into the DRP, the carbon content in the DRI remains constant. With increasing amount of hydrogen input, the carbon content of the DRI begins to decrease towards zero. As a consequence, the relative carbon dioxide reduction per unit hydrogen decreases beyond 35 energy-% of hydrogen input but the absolute emissions still decrease with an increasing injection of hydrogen (Martinez and Duarte, 2017).

Griesser and Buergler (2019) presented primary data from HBI use in a blast furnace, which on average produces 2500–2700 t_{HM}/day. The maximum HBI input was up to 160 kg/t_{HM}. They reported that per 100 kg/t_{HM} of HBI, the reducing agent rate (coke equivalent) could be decreased by about 25 kg/t_{HM}. Assuming a linear relationship as Yilmaz and Turek (2017) demonstrated, 400 kg/t_{HM} of HBI input would lead to a reduction of 100 kg/t_{HM} of coke equivalent. Considering an emission factor of about 3.3 kg CO_2 per kg of coke (WSA, 2020a), this input leads to a reduction of 330 kg CO_2/t_{HM} for the blast furnace. The results of the field tests prove that the made metallurgical models from both, Schmöle (2016) as well as Yilmaz and Turek (2017) deliver useable predictions. Griesser and Buergler (2019) also observed that the productivity [HM/hour] raised up to 10 % per 100 kg/t_{HM} HBI input.

The listed literatures describe for the considered scenarios the metallurgical changes of the blast furnace process, but they deliver not a holistic approach. Therefore, LCA studies and carbon footprint studies, respectively, if focusing only on the global warming potential, are required. These exist for several conventional steel production routes and also some limited future scenarios.

Norgate et al. (2007) assessed within an LCA approach the environmental impact of the metals copper, nickel, aluminium, lead, zinc, steel, stainless steel, and titanium. Tongpool et al. (2010) analysed the steel production in Thailand focusing on different downstream products. Within a material based LCA analysis, Neugebauer and Finkbeiner (2012) revealed the recycling potential of steel in a multi-recycling approach. Burchart-Korol (2013) presented an LCA of the steel production in Poland, considering the production through an integrated site and through a scrap-based EAF. Within an Italian LCA (Renzulli et al., 2016), human toxicity aspects of single processes from an integrated site are presented. Chisalita et al., 2019 and Petrescu et al. (2019) analysed the environmental impact of an integrated site with various techniques of CO_2 capture and storage. Backes et al. (2021) delivered an LCA approach of an integrated steel site based on primary data of thyssenkrupp Steel Europe.

Although, LCA studies and carbon footprint assessments are already widely applied within the steel industry, there are none for the scenarios, which are considered within this paper. Yet, there are papers (Schmöle, 2016; Yilmaz et al., 2017; Yilmaz and Turek, 2017; Griesser and Buergler, 2019), in which the metallurgical changes of the blast furnace process for the considered scenarios are described. Within this paper a carbon footprint assessment based on primary data is modelled and this status quo is enhanced with metallurgical models from the listed literature. Thereby a holistic carbon footprint assessment for the considered scenarios is presented so that the impact of these scenarios to reduce the global warming potential is evaluated from a global perspective.

2. Methodology

In order to present the potential of the considered transition scenarios towards climate-neutral steel production, the first step is the definition of a base line. Within this study, a typical primary blast furnace – basic oxygen furnace route based on primary data of tkSE, year 2018, is modelled. The implementation of the four scenarios (1) injection of natural gas into a blast furnace, (2) injection of hydrogen into a blast furnace, (3) use of natural gas-based hot briquetted iron (HBI) in a blast furnace, and (4) use of hydrogen-based HBI in a blast furnace affect the entire material and energy supply chain of an integrated steel site and its upstream chain. To reproduce these changes in a holistic and novel approach, metallurgical models from the literature, which give an explanation about the metallurgical changes of the blast furnace process, are integrated into the model of the status quo. Additional needed processes, like hydrogen production or the direct reduction of iron ores to HBI, are modelled within this study and integrated into the holistic approach. The focus of this paper is on the impact of the scenarios on climate change measured with the impact category Global Warming Potential (GWP).

Therefore, a product carbon footprint of hot-rolled coil according to ISO 14067 is applied to each scenario. The ISO norm 14067 is based on existing International Standards of life cycle assessment (LCA), ISO 14040 (2021) and ISO 14044 (2021). Whereas an LCA methodology must assess the environmental impacts on more than one impact category, a product carbon footprint assessment focuses on a single impact category, the climate change.

The present study follows the “cradle-to-gate” approach: all phases from raw-material extraction (cradle) to the finished product hot-rolled coil (gate) are included. The use phase of the product is consciously excluded, since the applications of hot-rolled coil (HRC) are numerous. After the use phase, the HRC turns into end-of-life (EoL) scrap, which can be recycled in an electric arc furnace (EAF) or within the primary route as feedstock for the basic oxygen furnace where a certain amount of scrap is needed as cooling material inside the highly exothermic process, anyway.

For the evaluation of the recycling potential, the World Steel Association (2011) methodology can be split into two pathways for recycling:

1. The recycled content approach: The scrap does not have an environmental footprint so neither a burden has to be taken into account when scrap is used nor the recycling at the end-of-life is considered.
2. The end-of-life recycling approach: Scrap has an environmental footprint so a burden has to be considered when scrap is used and credit is given when the material is recycled at the end-of-life.

Based on a life cycle inventory (LCI) value of the recycled content approach, the WSA (2011) presents a Formula to calculate the LCI value of the with-end-of-life approach:

$$LCI_{incl.EoL} = LCI_{recycled\ content} - (RR - S) \times Scrap_{LCI} \tag{1}$$

$LCI_{recycled\ content}$ is the calculated LCI value following the recycled content approach. The recycling rate RR [t Scrap/t_{HRC}] describes which share is recycled after the product’s life cycle. The scrap input S [t Scrap/t_{HRC}] is the amount of external scrap input. External means that the scrap is imported into the integrated site from the outside like other raw material. The internal accumulated scrap, which is recirculated in a close loop, does not need to be considered because it does not cross the system boundaries of the integrated site. The difference $RR - S$ describes the net scrap production of the primary steel production, which is after the product’s life cycle available on the market. The World Steel Association (2011) gives a methodology for calculating a carbon footprint of scrap based on the principle of an avoided burden. The methodology is based on the fact that steel production based on scrap via EAF-route is less emission-intensive than producing steel based on primary material. The net scrap production multiplied by the LCI value of scrap, calculated by the WSA (2011), results in a credit.

3. Case study

In the following a carbon footprint assessment according to ISO 14067:2019 for a conventional hot-rolled coil production and for transition scenarios towards climate-neutral steel production is presented. Within the first stage ‘goal and scope definition’ the scenarios are described from technical perspective and the system boundaries are presented. Made assumptions are specified within the supplementary material. Used data and chosen GHG emissions are reported in the second stage, the ‘life cycle inventory analysis’. The impact of the GHG emissions on the climate change expressed as Global Warming Potential (GWP) are shown in the third stage, the ‘life cycle impact assessment’. The presented results are discussed within the fourth stage ‘life cycle interpretation’. In a sensitivity analysis the impact of chosen assumptions and used metallurgical models on the carbon footprint are discussed.

3.1. Goal and scope definition

The goal of the present study is to determine the carbon footprint of transition scenarios towards a climate-neutral hot-rolled coil production within the BF-BOF route compared to the classical BF-BOF route. Thus, the use of alternative reducing agents as natural gas or hydrogen instead of pulverized coal, and in addition the use of pre-reduced HBI in a BF is investigated.

The aim of an integrated steel site is to reduce natural iron oxide to iron and to further process it into high-quality steel. Integrated sites usually include a sinter plant (SP), coke oven (CO), blast furnace (BF), basic oxygen furnace (BOF), continuous casting (CC), and subsequent hot-rolling (HR). Hot-rolled coil (HRC) can be transformed in further downstream processes like cold-rolling, galvanising or forming in several products with numerous functions. The declared unit of this carbon footprint of a product study is 1 t of hot-rolled coil. This paper focuses on data collect from the integrated site of *thyssenkrupp Steel Europe AG* (tkSE) in Duisburg, Germany of the year 2018. The processes of the integrated site, important raw materials, and produced co-products are shown in Fig. 1.

The reduction and melting of the iron oxide take place in a blast furnace on the basis of coal and coke. Coal can be replaced by hydrogen

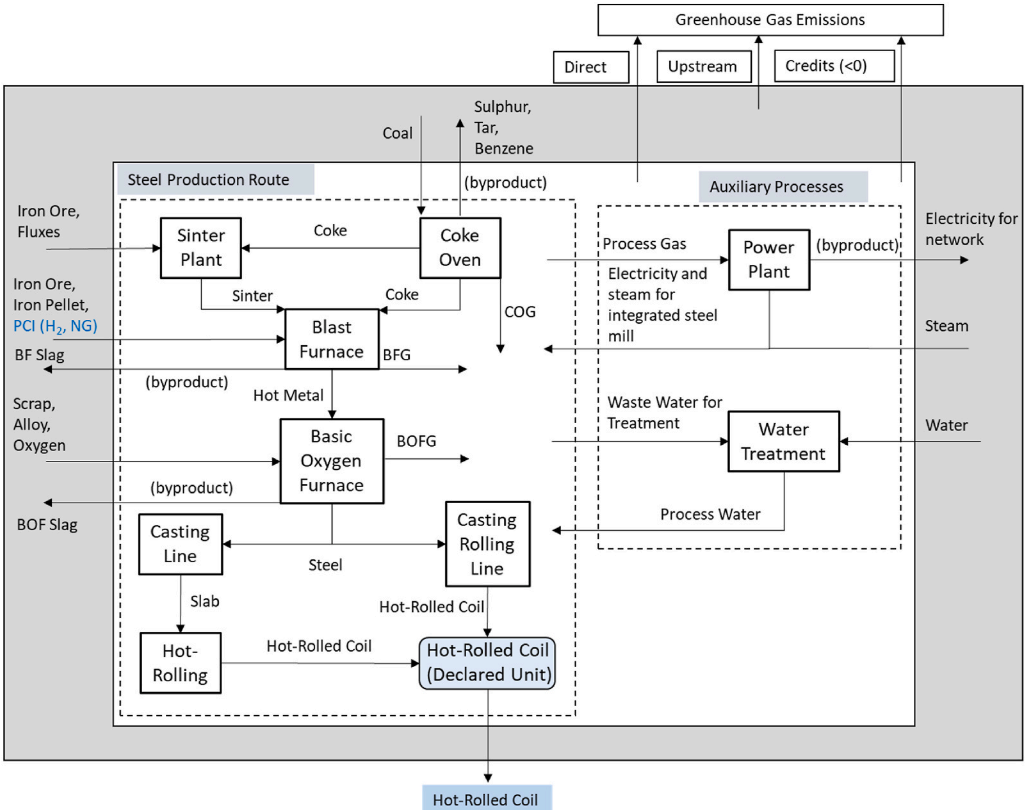

Fig. 1. System boundary overview. Within the Base Case pulverized coal is injected (PCI) into the blast furnace; within the scenarios natural gas (NG) and hydrogen, respectively (blue marked) are injected.

and natural gas to lower the carbon content within the blast furnace, which are two scenarios of this paper. The coke is made in coke ovens out of coal. Within this pyrolysis process the coke oven gas (COG), a hydrogen-rich off-gas, is generated. In addition, the by-products sulphur, tar, and benzene are produced. The feedstock natural fine iron ore cannot be directly reduced in a blast furnace, since a good gas permeability is required in the counter-current shaft furnace. Therefore, the fine iron ore is baked in a sinter plant to graded sinter. Finally, the iron feedstock graded sinter, lump ore, and iron ore pellets are reduced in a BF by coal and coke into hot metal. Besides the hot metal product, an oxidised slag remains. This slag is granulated and can be used as cement clinker for the cement industry. Inside the blast furnace (BF) the coal and coke are oxidised by injected hot blast and oxygen to carbon dioxide. At high temperatures and in the presence of carbon, carbon dioxide reacts to carbon monoxide according to the Boudouard reaction. These gases arise, reduce the counterflowing iron oxides and leave the blast furnace as blast furnace gas (BFG). Before the hot blast is injected into the BF, it is preheated in the hot blast stoves. These are auxiliary units of the BF. That is the reason why the hot blast stoves are included in the process BF, see Fig. 1. Within the basic oxygen furnace the hot metal is refined to crude steel. The blown oxygen binds the carbon of the hot metal and leaves the process as a carbon-monoxide-rich gas, the so-called basic oxygen furnace gas (BOFG). Since the oxidation reactions are highly exothermic, scrap is brought in as a cooling agent. An oxidised slag is produced, which is mainly used for road construction and as fertilizer. The crude steel is further processed to high-quality steel within the so-called secondary metallurgy. Thereby e.g. alloying elements are added, the steel is further homogenized, or the steel is vacuum treated. In Fig. 1, the secondary metallurgy is included in the process BOF. The liquid steel is cast over the continuous casting line into a strand and cut into slabs. The slabs normally are cooled down and preheated inside the hot strip mill and rolled to the product hot-rolled coil (HRC). In addition to a typically integrated steel mill, tkSE (year 2018) operates a casting-rolling line, where the liquid steel is cast into thin slabs, which are rolled in one heat into hot-rolled coils.

A characteristic, and at the same time, a strength of an integrated site is its complex energy network. The off-gases from the blast furnace, coke oven, and basic oxygen furnace are primarily used within the steel production route for heat supply. The excess off-gases are burnt in an integrated power plant for electricity and steam production, which are used within the integrated site. When considering the processes until the product hot-rolled coil, the produced electricity by the off-gases exceeds the plant demand so an amount of electricity can be introduced into the national greed.

Besides the use of alternative reducing agents within the blast furnace, another possibility to reduce the required carbon content inside the blast furnace is to replace iron ore with pre-reduced iron pellets in the form of HBI, see Fig. 2.

The gas-based direct reduction of the iron ore pellets to DRI/HBI takes place in a shaft furnace (Sarkar et al., 2018; Duarte et al., 2008). Compared with the porous DRI the structure of HBI is much more compact. Thus, re-oxidation reactions in the upper shaft areas of the blast furnace with higher oxygen partial pressures can be avoided (Schmöle and Lüngen, 2007). Both natural gas and hydrogen can serve as reducing agents within the DR plant amongst other gases.

The hydrogen is assumed to be produced via water electrolysis driven by a renewable German energy grid mix from the year 2018 according to the Environment Agency (Umweltbundesamt, 2019). As renewable energy sources electricity from wind power, photovoltaics, biogas, biomass, hydropower, and geothermal energy are used.

A summary of the scenarios described is given in Table 1:

The main assumptions for these scenarios, in Table 1, are reported within the supplementary materials.

For assessing the production of co-products, which are used outside

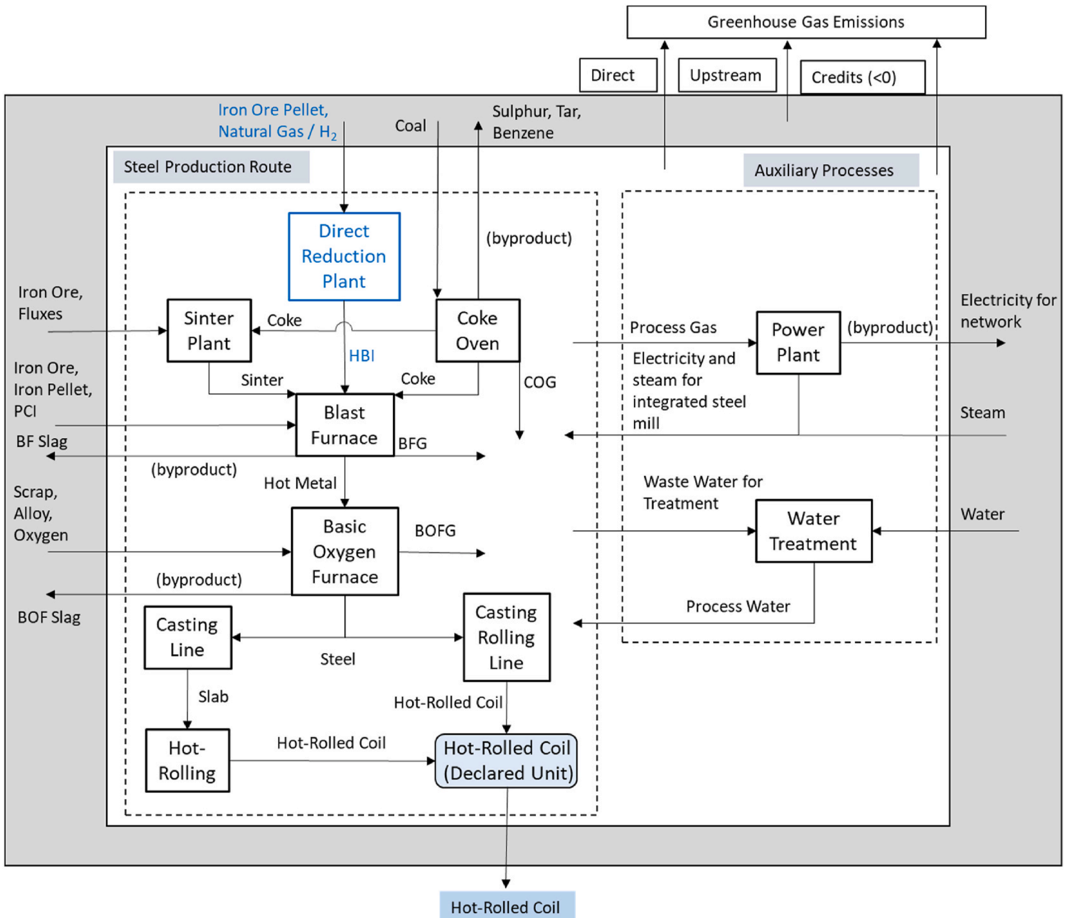

Fig. 2. System boundary of the scenarios natural gas-based and H_2-based hot briquetted iron (HBI) input in a blast furnace (BF). The changes compared to the base case of Fig. 1 are marked (blue).

Table 1
Scenario overview.

Scenario	Scenario Description
Base Case	Hot-rolled coil production via conventional blast furnace – basic oxygen furnace (BF-BOF) route of an integrated steel site based on *thyssenkrupp Steel Europe AG* in Duisburg, year 2018
NG in BF	Natural gas injection into a BF replaces pulverized coal injection
H_2 in BF	Hydrogen injection into a BF replaces pulverized coal injection. The hydrogen is modelled to be produced via water electrolysis driven by a renewable energy mix from Germany, year 2018.
NG-HBI in BF	Iron ore pellets are reduced to direct reduced iron (DRI) by natural gas in a direct reduction plant and briquetted to hot briquetted iron (HBI). The HBI is subsequently used in a BF.
H_2-HBI in BF	Iron ore pellets are reduced to DRI by hydrogen in a direct reduction plant and briquetted to HBI. The HBI is subsequently used in a BF.

the integrated steel mill, the method of system expansion is chosen. According to ISO 14044 (2021), system expansion is suggested to avoid allocation. Co-products, which substitute primarily production of products, save emissions within another industry. Therefore, credit is given following the avoided burden approach (Klöpffer and Grahl, 2014). The co-products are shown in Fig. 1. The amount of given credit is according to the principles defined by the World Steel Association (2011).

Within the supplementary materials all used processes from the GaBi Databases are listed.

3.2. Life cycle inventory analysis

The data of the internal processes of the integrated site are based on tkSE in Duisburg, year 2018. According to the European Union Emissions Trading System (EU-ETS), tkSE has to report its direct GHG emissions the German Emission Trading Authority (German: Deutsche Emissionshandelsstelle - DEHSt) annually. Therefore all carbon and iron feedstock, which enters and leaves the integrated steel site is measured and recorded. Amounts of used input materials, which are not considered in the EU-ETS, are accounted by the controlling and procurement departments of tkSE.

The data of the gas based direct reduction are determined within an internal study by tkSE (2020). The data are mostly in line with the data presented by Duarte et al. (2008) and Sarkar et al., 2018. The considered scenarios for GHG reduction are based on the Base Case and are enhanced with metallurgical models from the literature, which report the emission reduction of a blast furnace for the considered scenarios (Table 2). The emissions from mining, production, and transport of raw materials are taken from GaBi LCA databases (version SP40, year 2020).

Table 2
Operation modes of the considered scenarios according to Table 1. The metallurgical models are based on Schmöle (2016). The carbon dioxide emissions result of the carbon input into the blast furnace and are emitted at the processes where the blast furnace gas and the basic oxygen furnace gas are incinerated.

Input in BF	Base Case	NG in BF	H_2 in BF	HBI in BF
PCI [kg/t_{HM}]	200			127
Coke [kg/t_{HM}]	295	367	392	235
NG [kg/t_{HM}]		100		
H_2 [kg/t_{HM}]			40	
HBI [kg/t_{HM}]				400
Output				
CO_2 [kg/t_{HM}]	1527	1421	1235	1150

The LCA software GaBi (version 10.0.0.71) is delivered by ©Sphera Solutions GmbH. Credits for co-products are rated by GaBi databases, as well.

For describing the changed operation mode of the BF when injecting natural gas or hydrogen and also when using HBI in the BF, this paper leans on the metallurgical models by Schmöle (2016), whose key results are presented in Table 2.

For a better understanding of the origin of emissions, the contributions to the overall GHG-values are summed-up in sub categories.

1. Direct emissions: These emissions are emitted directly by the internal processes of the integrated steel site. The internal processes are visualized in Fig. 1 within the inner white zone.
2. Upstream emissions: These emissions result from mining, production, and transport of input materials to Germany. Important raw materials are visualized in Fig. 1 within the outer grey zone.
3. Credits for co-products: Co-products substitute primarily produced products from other industries and so avoid emissions. Therefore, credit is given according the LCA method of system expansion. The co-products result from the internal processes, which are visualized in Fig. 1 within the inner white zone.

This classification can also help to derive measures to further decrease the GHG emissions presented. Some chosen LCI results of the conventional Base Case are presented in Table 3. The total emissions are the sum of direct emissions, upstream emissions, and credits for co-products.

Within the integrated site the carbon input is mainly emitted as carbon dioxide proving complete combustion processes. Only within the sinter plant relevant amounts of carbon monoxide are emitted for process-related reasons. The methane emissions are caused by the coal mining within the upstream processes.

3.3. Life cycle impact assessment (LCIA)

A carbon footprint of a product (CFP) assessment (ISO 14067, 2019) is in accordance with the international standards on life cycle assessment (LCA), ISO 14040 and ISO 14044 (2021). Within this study the impact assessment method CML 2001 (updated: January 2016) is used. This method includes the midpoint category GWP 100 which is based on factors developed by the IPCC (Acero et al., 2016).

Table 3
LCI results of the Base Case.

	Carbon dioxide [t/t_{HRC}]	Methane [t/t_{HRC}]	Carbon monoxide [t/t_{HRC}]
Direct emissions	1.9	0	0.014
Upstream emissions	0.44	4.0e-3	0
Credits for co-products	−0.36	0	0
Total emissions	2.0	4.0e-3	0.014

3.3.1. Life cycle impact assessment results

The results of the base case are presented with two figures. The absolute values of the reference case depend on assumptions, the methodology, and the accuracy of the secondary databases amongst others. Since for the future scenarios the same approaches are used as for the reference scenario, the comparisons are presented with three figures.

3.3.1.1. Base Case. The carbon footprint of hot-rolled coil produced over a typical integrated steel site is 2.1 t CO_2eq/t_{HRC}, see Fig. 3. The presented processes and categorisation are in accordance with Fig. 1.

In total, the listed processes in Fig. 3, account for more than 98.5 % of the considered processes. Processes with an impact of lower than 1 % are considered within the total GWP and also within the upstream pillar, but they are not listed within the graphic for reason of clarity. The sum of direct GHG emissions generate a GWP of 1.9 t CO_2eq/t_{HRC} and are the most significant part. A comparison with Table 3 demonstrates that the GWP of the internal processes of the integrated site are almost exclusively generated by carbon dioxide emissions. The main emitting processes are in decreasing order the power plant, blast furnace, coke oven, sinter plant and subsequent hot-rolling. For interpretation, it is important to distinguish where the emissions are emitted and where they are actually caused. As mentioned above, the emissions of the blast furnace, reported in the literature, are about 1.5 t CO_2/t_{HM}, which are the result of about 420 kg C input/t_{HM} (DIN EN, 19694–2, 2016). This carbon input leaves the BF over the blast furnace gas and the hot metal. The C content of the hot metal leaves the basic oxygen furnace as BOF gas. Finally, the 1.5 t CO_2/t_{HM} are emitted at those processes where the BFG and the BOFG are incinerated to use their calorific value. The directly emitted emissions of the blast furnace result from its hot-blast stoves where process gas is burned to heat up the hot blast. These emissions generate a GWP of 0.42 t CO_2eq/t_{HRC} of the BF, see Fig. 3.

The impact on the climate change generated by the upstream emissions add up to about 0.56 t CO_2eq/t_{HRC}. The credits for co-products add up to about 0.38 t CO_2eq/t_{HRC}. Especially, the use of the blast furnace slag within the cement industry is an environmental useful cross-functional cooperation. The significant impact of the upstream processes and of the credits for co-products demonstrate two important aspects: During the transformation towards carbon neutrality besides the direct emissions, the upstream emissions have to be reduced, as well. Furthermore, the environmental benefits of the cross-functional cooperation need to be taken into account to avoid a shift of emissions.

The results presented in Fig. 3 follow the recycled content approach whereby scrap input and recycling after the product's life cycle is not considered. To calculate the carbon footprint including the end-of-life phase, $LCI_{recycled\ content}$ from Formula (1), has to be set on the carbon footprint of the recycled content approach, which is 2.1 t CO_2eq/t_{HRC}, see Fig. 3. According to the assumptions made, the recycling rate *RR* is 0.95 t scrap/t_{HRC}. The external amount of scrap input *S* is 0.15 t/t_{HRC}. Relating to the database "GLO: Value of scrap [worldsteel 2019]", the GWP of scrap is 1.6 t CO_2eq/t scrap. The carbon footprint of HRC following the with-end-of life approach is equal to Formula (2):

$$GWP_{incl.EoL} = 2.1\ t\ CO_2eq/_{t\ HRC} - (0.95 - 0.15)\ t\ Scrap/_{t\ HRC} \times 1.6\ t\ CO_2eq/_{t\ Scrap} = 0.82\ t\ CO_2eq/_{t\ HRC} \quad (2)$$

It becomes apparent that the carbon footprint strongly depends on the chosen methodology for recycling. Following the recycled content approach where scrap does not have an environmental impact, the carbon footprint of HRC is about 2.1 t CO_2eq/t_{HRC}, see Fig. 3. Following the with-end-of-life approach the carbon footprint is 0.82 t CO_2eq/t_{HRC}, see Equation (2), since a credit is given for the net scrap production according to the principle of an avoided burden.

3.3.3.2. Injection of natural gas and hydrogen into a blast furnace.

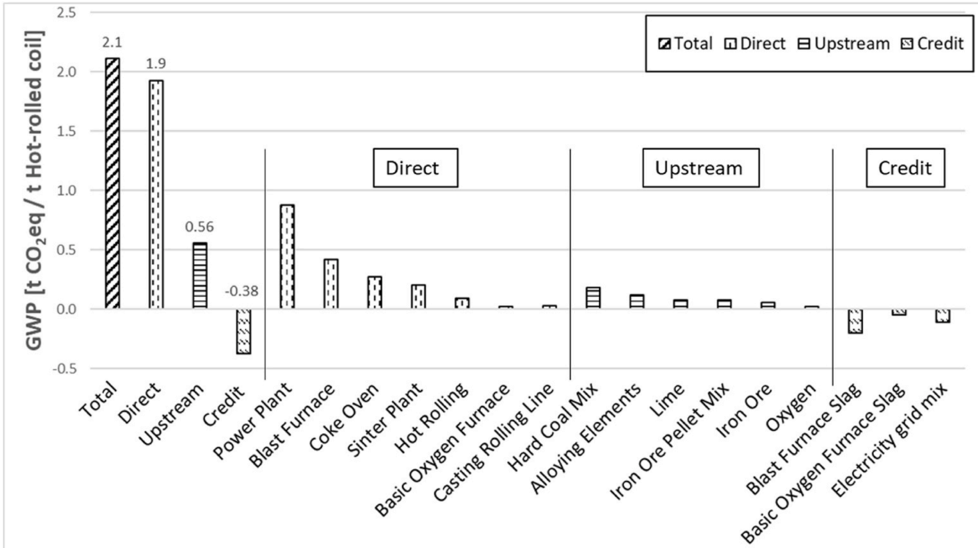

Fig. 3. Global warming potential (GWP) of HRC production over a conventional BF-BOF route (Base Case). Processes, which impact are lower than 1 % of the amount of the total GWP, are not listed. In total, the listed processes account for more than 98.5 % of the considered processes.

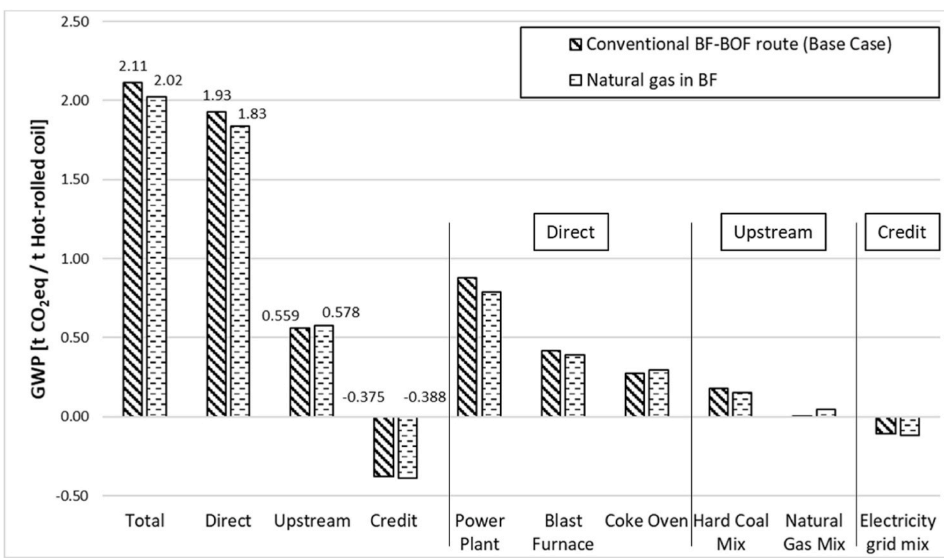

Fig. 4. Global warming potential (GWP) of HRC production over a conventional BF-BOF route (Base Case) compared to the scenario injection of natural gas in BF (Table 1). Only changed processes concerning the Base Case and processes which impacts are above 1 % of the total GWP are listed.

According to Table 1, the first two presented scenarios for GWP reduction are based on the replacement of pulverized coal injection (PCI) by natural gas (NG) and hydrogen respectively. The carbon footprint of hot-rolled coil, when 100 kg NG per tonnes of hot metal is injected into a BF (Table 2), is 2.02 t CO_2eq/t_{HRC}, see Fig. 4.

When injecting 40 kg hydrogen per tonnes of hot metal into a BF (Table 2), the carbon footprint of HRC is 1.93 t CO_2eq/t_{HRC}, see Fig. 5. Thereby the hydrogen is assumed to be made by water electrolysis driven by a German renewable electricity mix. The presented processes and categorisation are in accordance with Fig. 1.

The composition of the blast furnace gas shifts from carbon towards hydrogen when injecting natural gas or hydrogen into the blast furnace. As a result, the emission factor of the blast furnace gas (BFG) decreases compared to the Base Case. The BFG is incinerated at the power plant (PP), the hot stoves of the blast furnace, and the coke oven (CO). The emissions of the PP and of the BF decrease leading to a reduced GWP of these processes, see Figs. 4 and 5. Concerning the coke oven two counteracting effects lead to a nearly constant GWP of the coke production (scenario H_2 in BF) or even a slight increase (NG in BF). According to Table 2, an increased amount of coke is required within the blast furnace when the injection of natural gas or hydrogen replace pulverized coal completely in order to keep a constant adiabatic flame temperature and a constant thermal state of the furnace. On the other hand, the reduced emission factor of the BFG reduces the GWP caused by the coke oven [t CO_2eq/t of coke], where BFG is incinerated for heat supply. The additionally produced coke oven gas (COG) is incinerated at the coke oven and the power plant.

The GWP of the upstream process hard coal mix decreases in both scenarios. Again, two counteracting effects are responsible. Pulverized coal injection into the BF is replaced by the auxiliary reducing agents but the amount of coke increases and therefore more coal is needed for the coke oven process. Concerning the direct GHG emissions, the overall coal input into the integrated site is a key element.

The GWP of hydrogen is about 3.06 kg CO_2eq/kg hydrogen, see

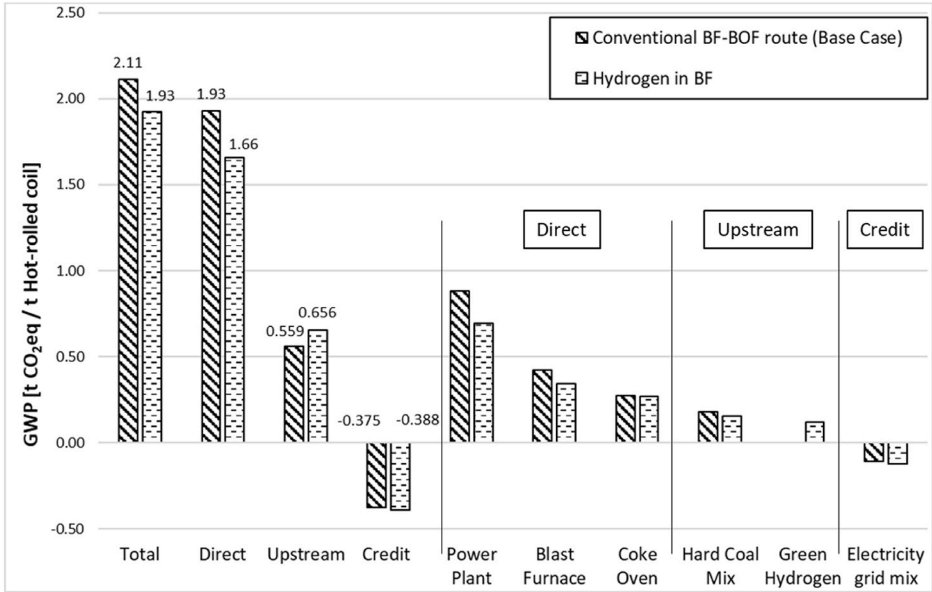

Fig. 5. Global warming potential (GWP) of HRC production over a conventional BF-BOF route (Base Case) compared to the scenario injection of hydrogen in BF (Table 1). Only changed processes concerning the Base Case and processes which impacts are above 1 % of the total GWP are listed.

supplementary material.

Due to the chosen assumption that the energetic amount of BFG remains constant the changed composition of the BFG has no effect on the electricity production within the power plant. Anyway, a slight increase in credit is observed because in both scenarios more coke oven gas is produced, due to more coke production.

Concerning the end-of-life approach the carbon footprint of HRC can be calculated according to Formula (3) and (4):

$$GWP(NG\ in\ BF)_{incl.EoL} = \frac{2.0\ t\ CO_2eq}{t\ HRC} - \frac{(0.95-0.15)t\ Scrap}{t\ HRC} \times \frac{1.6\ t\ CO_2eq}{t\ Scrap} = \frac{0.72\ t\ CO_2eq}{t\ HRC} \tag{3}$$

$$GWP(H_2\ in\ BF)_{incl.EoL} = \frac{1.9\ t\ CO_2eq}{t\ HRC} - \frac{(0.95-0.15)t\ Scrap}{t\ HRC} \times \frac{1.6\ t\ CO_2eq}{t\ Scrap} = \frac{0.62\ t\ CO_2eq}{t\ HRC} \tag{4}$$

The Carbon footprint following the end-of-life recycling approach is equal to the carbon footprint following the recycled content approach reduced by a credit for the net scrap production. As demonstrated in the Base Case the carbon footprint strongly depends on the chosen recycling methodology.

3.3.3.3. Use of natural gas-based and hydrogen-based HBI in a blast furnace. The next two scenarios for GWP reduction base upon the use of 400 kg HBI/t_{HM} in a blast furnace according to the system boundaries of

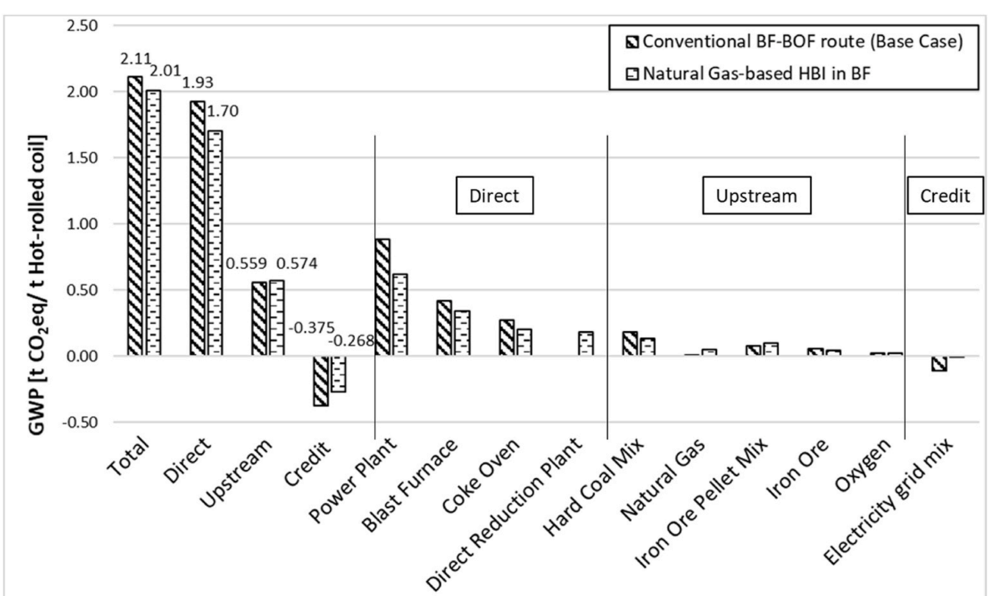

Fig. 6. Global warming potential (GWP) of HRC production over a conventional BF-BOF route (Base Case) compared to the scenario natural gas-based HBI input in a BF (Table 1). Only changed processes concerning the Base Case and processes which impacts are above 1 % of the total GWP are listed.

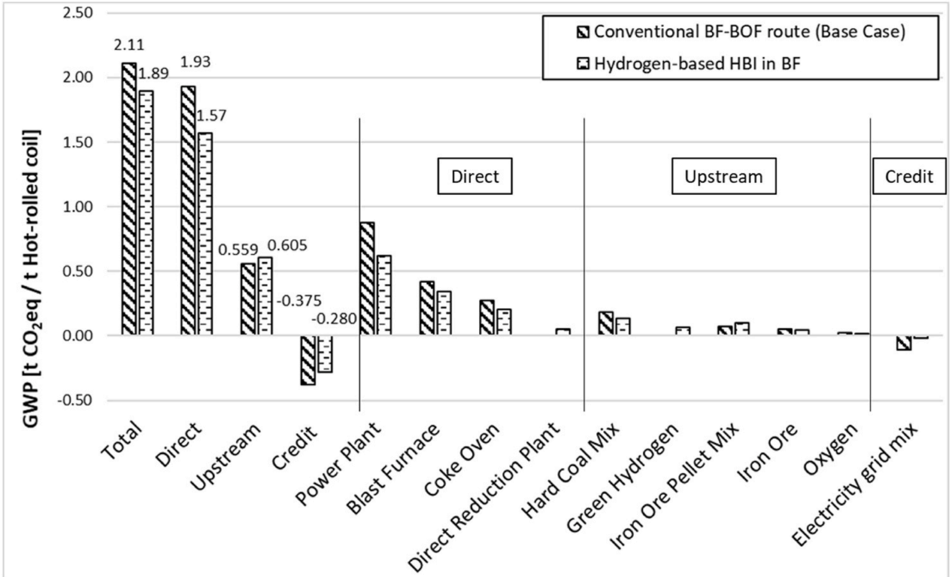

Fig. 7. Global warming potential (GWP) of HRC production over a conventional BF-BOF route (Base Case) compared to the scenario hydrogen-based HBI input in a BF (Table 1). Only changed processes concerning the Base Case and processes which impacts are above 1 % of the total GWP are listed.

Fig. 2 and data in Table 2. The carbon footprint of hot-rolled coil (HRC), when NG-based HBI is used in a BF, is 2.01 t CO_2eq/t_{HRC}, see Fig. 6. When H_2-based HBI is used in a BF, the carbon footprint of HRC is 1.89 t CO_2eq/t_{HRC}, see Fig. 7. Thereby the amount of hydrogen input is 22.1 kg/t_{HRC}. The distribution of the total GWP is in accordance with Fig. 2.

When inserting pre-reduced HBI in a blast furnace less carbon for reduction work is required. In addition, less mass has to be heated, since less mass of HBI is required to bring in the same amount of iron (Fe) than it is needed if the iron is introduced in form of iron ore pellets or lump ore, which are assumed to be displaced. Reduced carbon content leads to a lower amount of blast furnace gas (BFG) leaving the BF. Due to less coke demand the environmental impact of the coke oven process diminishes, see Figs. 6 and 7. Since less COG and BFG emerge, the GWP of the power plant decreases, as well in both scenarios. The direct emissions of the BF are caused by incineration of process gases at the BF's hot blast stoves to heat up the blast. Reduced carbon content in the BF goes along with less needed hot blast so that the required heat supply sinks, too and thereby the BF's emissions. The part of reducing the iron ore pellets to HBI takes the direct reduction plant (DRP). A share of achieved emission reduction concerning the BF-BOF route is shifted to the DRP. Anyway, in sum the direct emissions are reduced because in a DRP the iron ore pellets are reduced by natural gas or even by hydrogen made from electrolysis instead of coal and coke as it is in common use in a BF. In both cases of NG-HBI and H_2-HBI in BF natural gas is used for the gas preheater in the DRP.

The impact of the upstream processes remains in sum nearly constant. Concerning the reducing agents, the demand of hard coal sinks but instead NG or hydrogen for the direct reduction plant is needed. Since the DRP is fed exclusively with pellets there is a shift in iron feedstock from iron ores to iron ore pellets. The oxygen demand is partly shifted from the BF to the DRP. A negative effect on climate change is caused by less credit for electricity production, which results of decreasing BFG and COG. Considering the end-of-life phase leads to the following carbon footprints of HRC (Formula (5) & (6)):

$$GWP(NG - HBI\ in\ BF)_{incl.EoL} = \frac{2.0\ t\ CO_2eq}{t\ HRC} - \frac{(0.95 - 0.15)t\ Scrap}{t\ HRC} \times \frac{1.6\ t\ CO_2eq}{t\ Scrap} = \frac{0.72\ t\ CO_2eq}{t\ HRC} \quad (5)$$

$$GWP(H_2 - HBI\ in\ BF)_{incl.EoL} = \frac{1.9\ t\ CO_2eq}{t\ HRC} - \frac{(0.95 - 0.15)t\ Scrap}{t\ HRC} \times \frac{1.6\ t\ CO_2eq}{t\ Scrap} = \frac{0.62\ t\ CO_2eq}{t\ HRC} \quad (6)$$

Following the with-end-of-life approach the carbon footprint of HRC is significantly lower because of a given credit for the net scrap production.

3.4. Interpretation and sensitivity analysis

The data of the Base case are based on primary data, which are subject to strict monitoring as mentioned and can be regarded as good. Yet, for the transition scenarios, metallurgical models from the literature were used and assumptions had to be made. In the following the impact of the chosen underlying metallurgical models and the made assumptions are discussed.

In the shown scenarios NG-HBI (Fig. 6) and H_2-HBI (Fig. 7) in BF, the HBI replaces iron ore pellet and iron ore (as lump ore) in a blast furnace. The replacement of the iron feedstock sinter would be an option, as well. Owing to the fact that sinter has the highest carbon footprint of the iron feedstocks, the total GWP would be further decreased as shown in Table 4. The amount of replaced sinter is calculated by keeping the amount of iron (Fe) input in the BF constant. However, since the sinter serves as slag builder and the basicity of the blast furnace slag is adjusted by the sinter, this scenario from technical perspective can be a challenge. Yet it demonstrates that the carbon footprint reduction, which can be achieved by HBI input in a BF, lies within a range and an optimum between technical effort, environmental benefit, and economic profit can

Table 4
Sensitivity of replaced iron carrier by HBI input. The natural gas-based HBI (Fig. 6) and H_2-based HBI (Fig. 7) replace the iron feedstock iron ore pellets and iron ore (as lump ore) in a BF. The total GWP can be further decreased by replacing the iron feedstock sinter.

	NG-HBI in BF	H_2-HBI in BF	NG-HBI in BF	H_2-HBI in BF
HBI replaces in a BF:	Iron Ore Pellets & Iron Ore		Sinter	
Total GWP [t CO_2eq/t_{HRC}]	2.01	1.89	1.86	1.75

Table 5
Sensitivity of underlying metallurgical models concerning injection of hydrogen in a blast furnace (BF) on the carbon footprint.

Input/Output	Base Case	H_2 (ambient air temp.) in BF based on Schmöle (2016)	H2 (1200 °C) in BF based on Yilmaz et al. (2017)
Hydrogen [kg H_2/t_{HRC}]	0	39.7	27.3
Total GWP [t CO_2eq/t_{HRC}]	2.11	1.93	1.92
Efficiency of hydrogen [Δ kg CO_2eq/Δ kg H_2]	–	4.5	7.0

be found.

The sensitivity of the used underlying metallurgical models, which describe the changes in carbon dioxide emissions of the BF are examined in the following. As described earlier, Yilmaz et al. (2017) reported a hydrogen consumption of 27.5 kg H_2/t_{HM}, whereas Schmöle (2016) assumed 40 kg H_2/t_{HM} with nearly equal coke consumption and CO_2 reduction potential compared to a conventional BF operation mode with coal and coke. Yilmaz et al. (2017) assumed a hydrogen injection temperature of 1200 °C, whereas Schmöle (2016) did not assume a heat-up of the hydrogen. To estimate the total GWP based on the metallurgical model by Yilmaz et al. (2017) the GHG emissions of heating hydrogen from 0 °C up to 1200 °C have to be considered as well for a fair comparison. A rough estimation using the GaBi database "DE: Process steam from natural gas 90 %, ts" leads to an increase of GWP of about 1.2 kg CO_2eq/kg H_2 for a temperature increase from 0 °C to 1200 °C. The total GWP based on the two metallurgical models differ only about 0.01 t CO_2eq/t_{HRC}, see Table 5. The efficiency of hydrogen input concerning total GWP reduction [Δ kg CO_2eq/Δ kg of H_2] strongly depends on its injection temperature (Table 5). The more the injected hydrogen is preheated the more carbon dioxide emissions can be reduced per unit hydrogen input. Yet the assumption of Yilmaz et al. (2017) to heat-up the hydrogen on 1200 °C can be critical from a perspective of safety. These efficiency calculations are based on a linear reduction potential assumption. Possible different input assumptions of the metallurgical models disregarding coke, coal, and hydrogen, which would affect the upstream emissions, are not considered within this comparison.

Besides Schmöle (2016), also Yilmaz and Turek (2017) and Griesser and Buergler (2019) investigated the use of HBI in a BF as described earlier. Integrating the reduction potential of the different metallurgical models into the carbon footprint analysis leads to a carbon footprint from 2.01 t CO_2eq/t_{HRC} to 2.06 t CO_2eq/t_{HRC}, see Table 6. Thus, the total GWP is not much affected by the used underlying metallurgical model. Possible different assumptions of the metallurgical models concerning e.g. coal and coke input or other iron carrier inputs, which would affect the upstream emissions are not considered.

Table 6
Sensitivity of underlying metallurgical models concerning use of natural gas-based HBI in a blast furnace (BF) on the carbon footprint. The emission reduction of the blast furnace (BF) is the difference between the emissions resulting from a conventional BF operation mode and one with HBI input according to the underlying models.

Metallurgical model by	Emission difference of BF per t of HM [Δ kg CO_2/(400 kg HBI/t)]	Total GWP (NG-HBI in BF) per t of HRC [t CO_2eq/t]
Schmöle (2016)	377	2.01
Yilmaz and Turek (2017)	361	2.03
Griesser and Buergler (2019) (extrapolated)	330	2.06

Table 7
Impact of hydrogen input on the carbon footprint. The impact of hydrogen input into a blast furnace (H_2 in BF) is compared with a conventional BF operation mode (Base Case) with coal and coke. The impact of hydrogen input into a direct reduction plant (H_2-HBI in BF) is compared with a natural gas-based direct reduction (NG-HBI in BF) with subsequently use of the HBI in a BF.

	Base Case	H_2 in BF	NG-HBI in BF	H_2-HBI in BF
Input of hydrogen [kg H_2/t_{HRC}]	–	27.3–39.7	–	22.1
Total GWP [t CO_2eq/t_{HRC}]	2.11	1.92–1.93	2.01	1.89
Efficiency [Δ kg CO_2eq/Δ kg H_2]	–	4.5–7.0	–	5.4

3.4.1. Hydrogen yield related to GWP reduction

In two presented scenarios the use of hydrogen has been examined. The underlying calculations allow a direct comparison between the usage of hydrogen in a blast furnace and in a direct reduction plant, see Table 7. When hydrogen replaces pulverized coal in a BF the carbon footprint can be reduced about 4.5–7.0 kg CO_2eq/kg H_2 depending on the injection temperature (Table 5). In the case of the scenario NG-HBI in BF the total GWP can be reduced about 5.4 kg CO_2eq/kg H_2 when hydrogen replaces natural gas inside the DRP (Table 7). The difference of the total GWP between these scenarios is caused by firstly, different direct emissions of the DRP, secondly, different upstream emissions of the hydrogen and NG, and thirdly different electricity demands of the DRP. Therefore, the reduction potential of 5.4 kg CO_2eq/kg H_2 is independent of the replaced iron feedstock and also of the used underlying metallurgical model. Actually, it is also valid if the DRI is used in an electric arc furnace instead of a BF, when taking the assumption that the different reduction of NG or H_2, which can lead to different carbon contents of the DRI, does not affect the processes after the DRP. For both interpretations, H_2 in BF and HBI in BF a linear correlation between hydrogen input and emission reduction is assumed.

Even though from a metallurgical perspective, the hydrogen is used more efficiently in a DR plant because it is recirculated from the top gas into the shaft furnace, the emission reduction is not mandatory higher compared to the injection of the hydrogen into a BF. If the hydrogen is preheated before entering the BF the efficiency of hydrogen input into a BF even exceeds the input into a DRP. In the BF the hydrogen replaces coal, whereas in the DRP the hydrogen replaces natural gas, which emission factor is per se lower than the one coal.

The results of the sensitivity analysis demonstrate that the chosen metallurgical models and made assumptions can have a strong impact on the carbon footprint. Yet, they also demonstrate that there are several technical options to influence the total GWP.

4. Conclusion

The injection of hydrogen and natural gas, respectively as well as the use of hot briquetted iron (HBI) in a blast furnace open opportunities to reduce the carbon footprint of hot-rolled coil (HRC). Whereas the metallurgy and the corresponding direct emission reduction of the blast furnace (BF) process are well reported in the literature for these scenarios, there is no holistic assessment. The implementation of the scenarios changes the entire material and energy supply chain of an integrated steel site. New holistic findings of the impact of these complex changes on the climate change are revealed within this paper. Therefore, a carbon footprint of hot-rolled coil is presented for the base line and the transition scenarios. Within a sensitivity analysis, further reduction potentials have been assessed and identified.

The results are presented as cradle-to-gate approach. The emissions of the use phase are excluded but an end-of-life treatment is considered. Following the recycled content approach, where scrap does not have an environmental footprint, the global warming potential (GWP) of hot-rolled coil is 2.1 t CO_2eq/t_{HRC}. Following the with-end-of-life recycling approach, where an environmental footprint of scrap is considered, the GWP of HRC is 0.82 CO_2eq/t_{HRC}. This difference is caused by a credit for the net scrap production, according to the principle of an avoided burden.

In the first scenario, natural gas replaces the injection of pulverized coal in a blast furnace so that the carbon consumption of the blast furnace shifts partially from carbon to hydrogen. A carbon footprint reduction of 4 % compared to a conventional BF-BOF route is achieved referring to the recycled content approach. In the second scenario, hydrogen replaces the injection of pulverized coal in a blast furnace, leading to a reduction potential of 9 %. A carbon footprint of 3.06 kg CO_2eq/kg for hydrogen is given by modelling water electrolysis driven by a German renewable energy mix of year 2018. In a third scenario the reduction of iron oxides to direct reduced iron (DRI) by natural gas with subsequently use of the hot briquetted iron (HBI) in a blast furnace is discussed. A carbon footprint reduction between 5 % and 12 % is achieved. In the fourth scenario, hydrogen-based HBI is used in a blast furnace, leading to a reduction potential between 10 % and 17 %. The reduction potential strongly depends on the replaced iron feedstock, which is shown within a sensitivity analysis. In addition, different underlying metallurgical models are used as a basis and the results are compared. Special attention is given to the efficiency of hydrogen input concerning its potential to reduce the carbon footprint. The reduction potential of replacing pulverized coal by hydrogen in a blast furnace strongly depends on its injection temperature. The possible emission reduction by injecting hydrogen into a blast furnace can be higher than the reduction potential of using hydrogen in a direct reduction plant. Yet, a complete avoidance of GHG emissions cannot be completed within a BF as long as coke is needed as supporting matrix.

Limitations of this CFP study are that metallurgical models had to be used and assumptions had to be made for the considered future scenarios. Future technical field tests can improve the data quality and open new doors for reducing the impact of the steel production on climate change. With an improved data situation, this CFP study can be enhanced by an LCA study considering more impact categories than the climate change. Within a life cycle sustainability assessment (LCSA) also economic and social pillars of these scenarios could be investigated.

Overall, each of the presented scenarios has its merits to enable a stepwise transition towards a climate-neutral steel production. By injecting hydrogen into existing blast furnaces a demand is generated so that a market for hydrogen can be established. A temporary use of HBI into blast furnaces is a reasonable way to reduce GHG emissions until the technical structure of the transformation is completed and metallurgical challenges are solved. Thereby, continuous integration of direct reduction plants into an integrated steel site can be enabled.

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CRediT authorship contribution statement

Julian Suer: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Marzia Traverso:** Supervision, Project administration. **Frank Ahrenhold:** Supervision, Project administration.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128588.

References

ISO 14040, 2021. DIN EN ISO 14040:2021-02. Environmental Management – Life Cycle Assessment – Principles and Framework.

ISO 14044, 2021. DIN EN ISO 14044:2021-02. Environmental Management – Life Cycle Assessment – Requirements and Guidelines.

Acero, A.P., Rodriguez, C., Ciroth, A., 2016. LCIA Methods. Impact Assessment Methods in Life Cycle Assessment and Their Impact Categories.

Backes, J.G., Suer, J., Pauliks, N., Neugebauer, S., Traverso, M., 2021. Life cycle assessment of an integrated steel mill using primary manufacturing data: actual environmental profile. Sustainability 13 (6), 3443. https://doi.org/10.3390/su13063443.

Berger, Roland, 2020. The future of steelmaking. How the European Steel Industry Can Achieve Carbon Neutrality.

Bhaskar, A., Assadi, M., Somehsaraei, H.N., 2020. Decarbonization of the iron and steel industry with direct reduction of iron ore with green hydrogen. Energies 13 (3), 758. https://doi.org/10.3390/en13030758, 2020.

Burchart-Korol, D., 2013. Life cycle assessment of steel production in Poland: a case study. J. Clean. Prod. 54, 235–243. https://doi.org/10.1016/j.jclepro.2013.04.031, 2013.

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

DIN EN 19694-2, 2016. Stationary Source Emissions - Greenhouse Gas (GHG) Emissions in Energy-Intensive Industries - Part 2: Iron and Steel Industry.

Duarte, Pablo E., Becerra, Jorge, Lizcano, Carlos, Martinis, A., 2008. ENERGIRON direct reduction technology-economical, flexible, environmentally friendly. Acero Latinoam. 6, 52–58.

EU (2016): Proposal for a Regulation of the European Parliament and of the Council on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 for a resilient Energy Union and to meet commitments under the Paris Agreement and amending Regulation No 525/2013 of the European Parliament and the Council on a mechanism for monitoring and reporting greenhouse gas emissions and other information relevant to climate change. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52016PC0482&from=DE (accessed 16 February 2021).

Fischedick, M., Marzinkowski, J., Winzer, P., Weigel, M., 2014. Techno-economic evaluation of innovative steel production technologies. J. Clean. Prod. 84, 563–580. https://doi.org/10.1016/j.jclepro.2014.05.063.

Griesser, A., Buergler, Th, 2019. Use of HBI in blast furnace. BHM Berg-und Hüttenmännische Monatshefte 164 (7), 267–273. https://doi.org/10.1007/s00501-019-0865-6.

Hölling, M., Weng, M., Gellert, S., 2017. Bewertung der Herstellung von Eisenschwamm unter Verwendung von Wasserstoff. Stahl Eisen 137 (6), 47–53.

Klöpffer, W., Grahl, B., 2014. Life Cycle Assessment (LCA): a Guide to Best Practice. John Wiley & Sons.

Martinez, J., Duarte, P., 2017. Tenova HYL NEWS. (Accessed May 2017).

Neugebauer, S., Finkbeiner, M., 2012. Ökobilanz nach ISO 14040/44 für das Multirecycling von Stahl. Wirtschaftsvereinigung Stahl, Düsseldorf, Germany.

Norgate, T.E., Jahanshahi, S., Rankin, W.J., 2007. Assessing the environmental impact of metal production processes. J. Clean. Prod. 15, 8–9. https://doi.org/10.1016/j.jclepro.2006.06.018 (2007):838-848.

Pardo, N., Moya, J.A., 2013. Prospective scenarios on energy efficiency and CO2 emissions in the European Iron & Steel industry. Energy 54, 113–128. https://doi.org/10.1016/j.energy.2013.03.015.

Petrescu, L., Chisalita, D.A., Cormos, C.C., Manzolini, G., Cobden, P., Van Dijk, H.A.J., 2019. Life Cycle Assessment of SEWGS technology applied to integrated steel plants. Sustainability 11 (7), 1825. https://doi.org/10.3390/su11071825.

Renzulli, P.A., Notarnicola, B., Tassielli, G., Arcese, G., Di Capua, R., 2016. Life cycle assessment of steel produced in an Italian integrated steel mill. Sustainability 8 (8), 719. https://doi.org/10.3390/su8080719.

Sarkar, S., Bhattacharya, R., Roy, G.G., Sen, P.K., 2018. (2017): Modeling MIDREX based process configurations for energy and emission analysis. Steel Res. Int. 89 https://doi.org/10.1002/srin.201700248.

Schmöle, P., 2016. The blast furnace - fit for the future?. In: Stahl und Eisen, vol. 136, pp. 31–40.

Schmöle, P., Lüngen, H.B., 2007. Use of pre-reduced material in the blast furnace: metallurgical, ecological and economic aspects. In: Stahl und Eisen, vol. 127, pp. 47–54.

IEA, 2020. Iron and Steel Technology Roadmap - towards More Sustainable Steelmaking. OECD Publishing, Paris, pp. 38–43. https://doi.org/10.1787/3dcc2a1b-en.
tkSE, 2020. Internal Communication about the Operation of Direct Reduction Plants. thyssenkrupp Steel Europe AG, Duisburg.
Tongpool, R., Jirajariyavech, A., Yuvaniyama, C., Mungcharoen, T., 2010. Analysis of steel production in Thailand: environmental impacts and solutions. Energy 35 (10), 4192–4200. https://doi.org/10.1016/j.energy.2010.07.003.
Umweltbundesamt, 2019. Erneuerbare energien in deutschland. Daten zur Entwicklung im Jahr 2018. ISSN: 2363-829X.
Vogl, V., Åhman, M., Nilsson, L.J., 2018. Assessment of hydrogen direct reduction for fossil-free steelmaking. J. Clean. Prod. 203, 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279.
World Steel Association, 2011. Life Cycle Assessment Methodology Report.
World Steel Association, 2020. World Steel in Figures.
Wörtler, M., Schuler, F., Voigt, N., Schmidt, T., Dahlmann, P., Lüngen, H.B., Ghenda, J., 2013. Steel's Contribution to a Low-Carbon Europe 2050. Technical and Economic Analysis of the Sector's CO2 Abatement Potential.
Yilmaz, C., Turek, T., 2017. Modeling and simulation of the use of direct reduced iron in a blast furnace to reduce carbon dioxide emissions. J. Clean. Prod. 164, 1519–1530. https://doi.org/10.1016/j.jclepro.2017.07.043.
Yilmaz, C., Wendelstorf, J., Turek, T., 2017. Modeling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions. J. Clean. Prod. 154, 488–501. https://doi.org/10.1016/j.jclepro.2017.03.162.

2.3 Carbon footprint and energy transformation analysis of steel produced via a direct reduction plant with an integrated electric melting unit

This section presents publication III: 'Suer, J., Ahrenhold, F., Traverso, M.: Carbon Footprint and Energy Transformation Analysis of Steel Produced via a Direct Reduction Plant with an Integrated Electric Melting Unit. Journal of Sustainable Metallurgy (2022). Published August 2022. https://doi.org/10.1007/s40831-022-00585-x.'

The publication focuses on the PCF assessment of a natural gas and a hydrogen-based DR plant. The innovative route of an electric melting unit is technically assessed. In an electric melting unit the DRI is melted and carburized to hot metal. Typical aggregates are a submerged arc furnace or an open (slag) bath furnace. The hot metal substitutes the hot metal from current blast furnaces. Thus, the processes from BOF downwards do not need to change. Metallurgical opportunities and challenges are discussed. The energy transition from a coal-based BF route towards a hydrogen and electricity-based DR route is highlighted in five steps.

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RESEARCH ARTICLE

Carbon Footprint and Energy Transformation Analysis of Steel Produced via a Direct Reduction Plant with an Integrated Electric Melting Unit

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Abstract
The production of flat steel products is commonly linked to highly integrated sites, which include hot metal generation via the blast furnace, basic oxygen furnace (BOF), continuous casting, and subsequent hot-rolling. In order to reach carbon neutrality a shift away from traditional carbon-based metallurgy is required within the next decades. Direct reduction (DR) plants are capable to support this transition and allow even a stepwise reduction in CO_2 emissions. Nevertheless, the implementation of these DR plants into integrated metallurgical plants includes various challenges. Besides metallurgy, product quality, and logistics, special attention is given on future energy demand. On the basis of carbon footprint methodology (ISO 14067:2019) different scenarios of a stepwise transition are evaluated and values of possible CO_2equivalent (CO_2eq) reduction are coupled with the demand of hydrogen, electricity, natural gas, and coal. While the traditional blast furnace—BOF route delivers a surplus of electricity in the range of 0.7 MJ/kg hot-rolled coil; this surplus turns into a deficit of about 17 MJ/kg hot-rolled coil for a hydrogen-based direct reduction with an integrated electric melting unit. On the other hand, while the product carbon footprint of the blast furnace-related production route is 2.1 kg CO_2eq/kg hot-rolled coil; this footprint can be reduced to 0.76 kg CO_2eq/kg hot-rolled coil for the hydrogen-related route, provided that the electricity input is from renewable energies. Thereby the direct impact of the processes of the integrated site can even be reduced to 0.15 kg CO_2eq/kg hot-rolled coil. Yet, if the electricity input has a carbon footprint of the current German or European electricity grid mix, the respective carbon footprint of hot-rolled coil even increases up to 3.0 kg CO_2eq/kg hot-rolled coil. This underlines the importance of the availability of renewable energies.

The contributing editor for this article was Christina Meskers.

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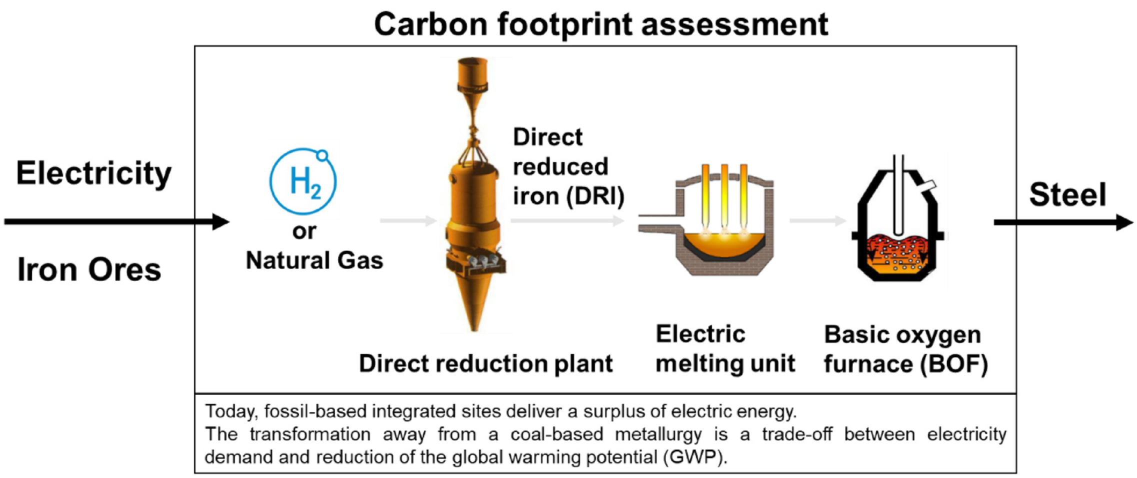
Graphical Abstract



Keywords Carbon footprint · Direct reduction plants · Electric melting unit · Energy transformation · Hydrogen · Integrated steel site

Abbreviations

BF	Blast furnace
BOF	Basic oxygen furnace
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
DR	Direct reduction
DRI	Direct reduced iron
EAF	Electric arc furnace
GHG	Greenhouse gas
GWP	Global warming potential
H_2	Hydrogen
HBI	Hot briquetted Iron
HRC	Hot-rolled coil
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment
LCI	Life cycle inventory
LHV	Lower heating value
NG	Natural gas
PCF	Product carbon footprint
tkSE	Thyssenkrupp Steel Europe AG

Introduction

The production of flat steel products is commonly linked to highly integrated sites. These sites normally include hot metal generation via the blast furnace, BOF, continuous casting, and subsequent hot-rolling. Including DR plants offers various new opportunities to these sites, especially a wide reduction in CO_2eq emissions [1, 2]. Nevertheless, the implementation of DR plants into integrated metallurgical plants include various challenges. Metallurgical aspects need to be considered to maintain product quality, which reflects customer demand. Effects on the sites, internal and external energy network and on-site logistics must be evaluated and handled. Therefore, direct reduction with pure hydrogen and with natural gas as an interim solution combined with electrically melting are discussed.

Integrated steelmaking sites on the basis of blast furnace technology still account for 58% of steel production within the European Union (28) and even 73% of the worldwide steel is provided via the blast furnace route [3]. About 26% of the worldwide steel is produced by scrap recycling via an electric arc furnace (EAF) [3]. In sum, the energy-intensive steel industry is a large emitter of CO_2 emissions accounting to about 7% of total worldwide anthropogenic emissions [4]. Although steel is a material with a highly effective recycling loop, the predicted worldwide demand of steel until 2050 and beyond needs considerable input of iron ore, since the increasing demand cannot be filled by scrap recycling alone [4].

It is presumed here that.

- Integrated sites persist to incorporate iron ore into the production cycle of steel.
- Integrated sites will continue to produce high purity steel qualities with superior surfaces, which set the standards in premium flat products.
- The coal-based metallurgy of blast furnaces within the integrated sites causes an inacceptable high carbon

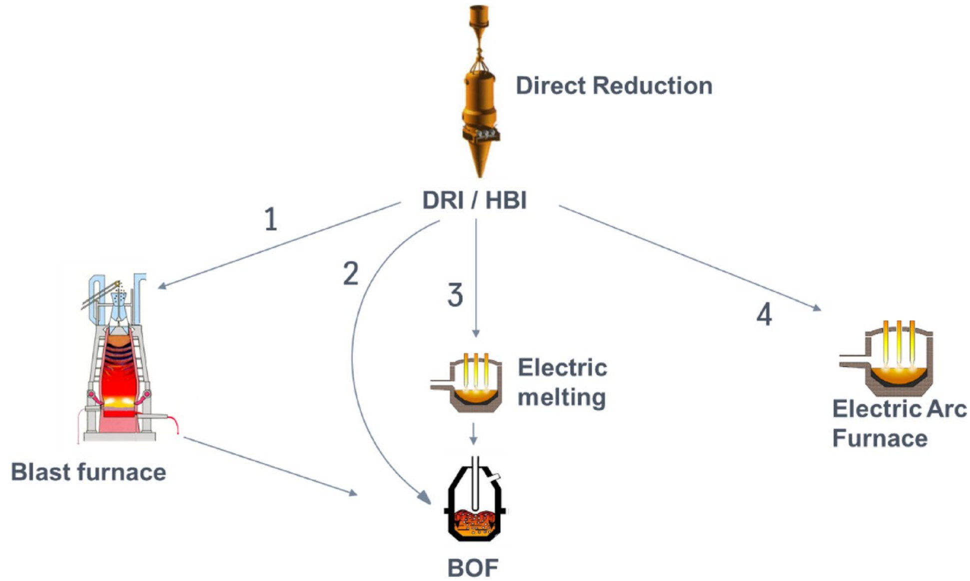


Fig. 1 Possible Flow schemes for Direct reduced Iron/Hot briquetted Iron (DRI/HBI) at integrated sites

footprint. Coal-based reduction of ore needs to be replaced by carbon reduced techniques.

In previous years many different technologies have been suggested, which show the potential to make classical blast furnace technology obsolete. Most of these technologies need further development, and thus are incapable to start any transition process in time [5]. DR technology on the contrary is fully developed and commercially available. DR modules have now reached capacities, which allow replacing blast furnaces on a like for like basis. Modules above 2.5 Million tons of output per year are the state of the art already today, and future installations are likely to reach even higher capacities [1]. Although a pure hydrogen-based shaft furnace direct reduction process in a large scale has not been realized yet the concept is technically feasible and has already been proven for a large-scale hydrogen-rich (H_2 content of 55–86%) shaft furnace direct reduction process [2].

DR technology and direct reduced iron (DRI) material can be included into the existing material streams of existing plants in different ways. Figure 1 shows possible outbound material streams of DR plants**.** Several possible paths are described: the first one, DRI or in form of hot briquetted iron (HBI) material can provide feedstock to an existing blast furnace (BF), see arrow 1. HBI would be the natural choice in this case as DRI usage bears the risk of re-oxidation in the upper parts of the BF. Although the required carbon input into the blast furnace can be reduced by HBI input, the energy for melting still originates from coal. Subsequently reduction in carbon dioxide emissions is not complete [6].

Path 2 in Fig. 1 uses DRI or HBI as a scrap substitute at the BOF. Reduction in CO_2eq emissions are limited as is the scrap rate in BOF steelmaking. Path 3 overcomes the limitations of path 2 by pre-melting DRI or HBI in an electric melting unit. This melt replaces hot metal and therefore makes blast furnaces obsolete. The melting unit process will still require some metallurgical carbon, which needs additional attention to reach decarbonized steel production. Path 4 uses a classical electric arc furnace (EAF) to melt DRI/HBI and scrap. This straightforward concept replaces not only blast furnaces but also BOFs. Some metallurgical carbon might be required here as well to preserve advantages of a foaming slag within the EAF [7].

In order to produce high quality steel grades lowest levels of nitrogen, phosphor, or carbon can be mandatory [8, 9]. Murphy discusses various aspects of nitrogen control in EAF steelmaking and concludes, “Technological solution is required to enable EAF to compete with BOF route on all grades” [8]. The problem to reach lowest nitrogen contents becomes even more difficult when lowest carbon content is simultaneously necessary [8, 9]. So far, no economically reasonable solution is available, while such steel grades are widely used in automotive applications, electro-mobility and deep drawing [9]. This can be a limitation for path 4 in Fig. 1 (EAF steelmaking).

In a direct comparison of converter vs. EAF steelmaking the following matters: The integrated steelmaking based on BOF process reaches nitrogen values between 20 and 40 ppm even in final products [9]. The BOF vessel shields the melt well against the surrounding atmosphere and it takes additional high-volume streams of carbon monoxide to keep nitrogen low throughout the blowing process. EAF modules do not present a similar air tightness and reach typical nitrogen values between 40 and 90 ppm [9].

Focus of this paper is the environmental evaluation of a DR plant combined with an electric melting unit (Fig. 1, path 3). The life cycle assessment (LCA) according to

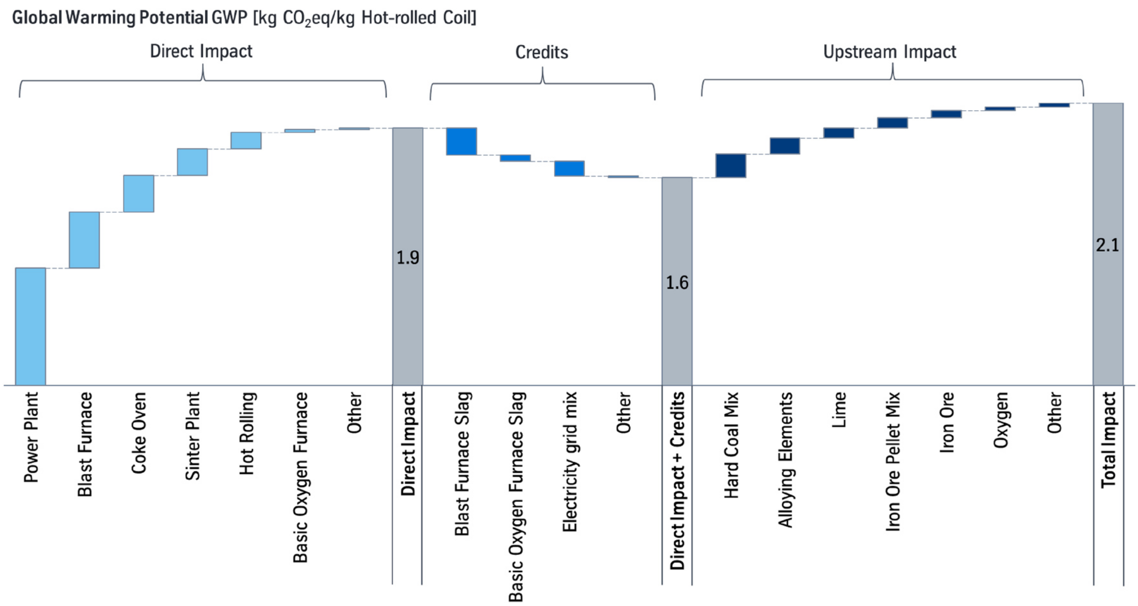


Fig. 2 Global warming potential (GWP) of hot-rolled coil, produced over a conventional BF-BOF route (Base Case). Data base 2018 [27]

the international standards ISO 14040/44 [10, 11] is an established standardized methodology to determine the environmental influence of products. Within an LCA material and energy-related flows as well as environmental impacts are assessed in a holistic approach. LCAs for the current steel production are already widely applied in steel industry:

Norgate et al. [12], Burchart-Korol [13], Renzulli et al. [14], Chisalita et al. [15], and Backes et al. [16] presented LCAs for conventional steel production via the currently most common BF-BOF route. The presented product carbon footprints range from 1.6 kg CO_2eq/kg steel up to 2.3 kg CO_2eq/kg steel. Besides the product steel, some studies relate the environmental impact to the product hot-rolled coil. Different scrap rates, quality of raw materials, technical production sites, and methodological assumptions explain the differences.

LCAs for steel production via DR plants with electrically melting are not available in literature. Yet, there are environmental analyses with focus on carbon dioxide emissions and energy consumptions of steel production: Larsson et al. [17], Barati et al. [18], Harada and Tanka [19], Arens et al. [20], and Sarkar et al. [21] analyzed the carbon dioxide emissions and some of them the energy consumption of steel production via a natural gas-based direct reduction process combined with an EAF. Within the studies, the EAF is charged with different mixes of scrap and DRI. The carbon dioxide emissions range from 0.4 kg CO_2/kg steel for an only scrap-based EAF operation up to 1.5 kg CO_2/kg steel for an only DRI-based EAF operation. In the same way the reported energy consumptions range from 4 MJ/kg steel up to 23 MJ/kg steel. A steel production via a hydrogen-based direct reduction process combined with an EAF is presented by Fischedick et al. [22], Otto et al. [23], Vogl et al. [24], and Bhaskar et al. [25]. The carbon dioxide emissions depend significantly on the underlying grid emission factor of the used electricity mix.

Although most of the studies are comprehensive studies, none of these follow the LCA or product carbon footprint (PCF) methodology according to ISO 14040/44 [10, 11] and ISO 14067 [26], respectively. The presented study fills this gap by providing a holistic carbon footprint assessment according to ISO 14067 for this innovative steel production route and all environmental impacts from raw material acquisition to the product hot-rolled coil are included. In addition, the novel concept of incorporating an electric melting unit into integrated sites is discussed and analyzed, whereas the focus of the available literature is on classical EAFs.

The presented study expands the study of Suer et al. [27], in which a PCF for hot-rolled coil produced via a conventional BF-BOF route is assessed. In Fig. 2, the results of the Base Case of the previous study are summarized.[1] The Base Case of an integrated steel production via BF-BOF route amounts an overall carbon footprint of 2.1 kg CO_2eq/kg hot-rolled coil. Individual contributions are split in sub-categories:

[1] The Base Case of the previous study [27] is also used as Base Case for this study. The previous study was done by the same authors of this study so the same methodological approach was followed.

The direct impact describes the processes of the integrated steel site and add up to 1.9 kg CO_2eq/kg hot-rolled coil (HRC). The impacts are attributed to the processes, where the respective emissions are emitted and not where they are caused. E.g., the impact of the power plant is caused by the processes, in which the process gases are produced, which are incinerated in the power plant. Turning off the power plant could not eliminate the emissions resulting from the process gases, but these would have to be incinerated somewhere else.

Following the principle of system expansion credits are given for the co-products [11, 26], which reduce the global warming potential (GWP) to about 1.6 kg CO_2eq/kg HRC. Especially, the use of the blast furnace slag within the cement industry is an environmental useful cross-functional cooperation. These benefits need to be taken into account to avoid unnoticed shift of environmental impacts. The impact of the upstream processes add up to about 0.56 kg CO_2eq/kg HRC [27]. The result of the previous study of 2.1 kg CO_2eq/kg hot-rolled coil [27] is consistent to the carbon footprint from the GaBi database of 2.0 kg CO_2eq/kg slab.[2]

In the previous study based on the results of the Base Case, modified BF operations are analyzed like the injection of hydrogen and the use of HBI in a BF. These measurements enable a reduced carbon input into the BF but the coke cannot be replaced, completely. Yet, the injection of hydrogen into existing blast furnaces can push the establishment of a hydrogen market and infrastructure and reduce the GHG emissions of the BF-BOF route. The use of HBI in a BF is a first step to integrate DR plants into an integrated steel site. [27]

Thus, these scenarios can function as intermediate scenarios towards a further CO_2eq-reduced steel production. This goal is described in this paper by presenting a PCF for a natural gas-based and a hydrogen-based DR plant with an electric melting unit.

Methodology

Since the data availability of future scenarios is not as technical mature as for conventional steel production, the focus of this paper lies on a single environmental impact category: climate change. Therefore the sum of greenhouse gas (GHG) emissions and removals of a product system, expressed as CO_2eq are assessed. The mass of a GHG is converted into CO_2eq by multiplying the mass of the GHG by the respective GWP. The GWP of a GHG characterizes its impact on the climate change in comparison to CO_2. Since GHG have different life spans in the atmosphere a time horizon has to be defined. Within this paper the GWP 100 is used to represent the impact of the GHG emissions on climate change for a time horizon of 100 years. [26]

A carbon footprint of a product assessment according to ISO 14067 [26] is conform to an LCA according to ISO 14040 [10] and 14044 [11]. Whereas within an LCA several impact categories are assessed, the focus of a carbon footprint assessment is on the climate change as the single impact category [26]. The impact category climate change is a so-called midpoint category. The resulting effects from climate change, e.g. extreme weather events, are called endpoint categories [28] and are analysed e.g., by the IPCC [29].

Within this paper a so-called cradle-to-gate approach is followed. Thus, GHG emissions of a life cycle from mining of raw materials and energy carriers, transport, and production processes are included, which are required to produce the considered product [26]. The declared unit is 1 kg of hot-rolled coil. Further downstream treatment of the hot-rolled coil and the use phase are consciously excluded because steel products have several applications. Since the downstream treatment and the use phase are not affected by the considered scenarios, the cradle-to-gate approach is adequate to evaluate the impact of the scenarios on climate change.

The carbon footprint of all considered scenarios are based on the same methodology and databases.[3] Following the methodology of a recycled content approach scrap does not have an environmental footprint and is considered as burden-free [30]. The emissions from scrap collection, sorting, and processing are not included in this study. For conventional steel production these emissions are 'generally negligible' [30]. This is also assumed for the future scenarios, which is a limitation of this study. However, this convention affects the absolute values of the scenarios but the relative differences between the scenarios are not affected, since the scrap input into the BOF is equal in all considered scenarios. The internal accumulated scrap until the product hot-rolled coil is recycled completely in the BOF.

For assessing the production of co-products, which are used outside the integrated steel mill, the method of system expansion is chosen. Thus, it is assumed that the co-product substitutes a primary production of the product and therefore a credit is given [11, 26]. Since the given credits depend on the environmental impacts of the substituted primarily produced products, these values have a degree of uncertainty when considering future scenarios. Therefore, like in Fig. 2 the individual contributions of the processes are presented in this paper so that each impact is transparent. Thus, the

[2] GaBi database, 2021.1 (DE: BF Steel billet/slab/bloom).

[3] incl. the Base Case (Fig. 2), which was done by the same authors of this paper [27].

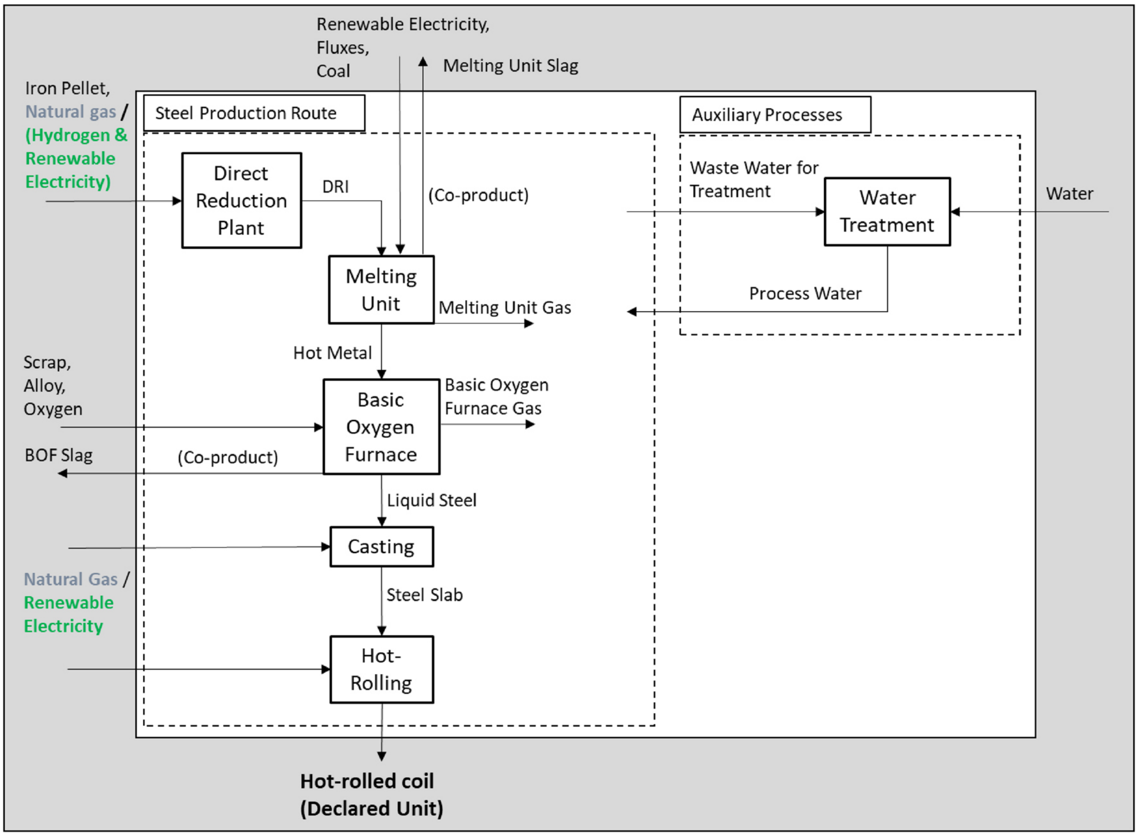


Fig. 3 System boundary definition and major material streams of the future scenarios: natural gas (NG-Case; grey input) or hydrogen-based (H_2-Case; green input) direct reduction with an integrated electric melting unit. White zone: processes of the integrated steel site. Grey zone: inputs and outputs of the integrated steel site. The process basic oxygen furnace (BOF) includes the secondary metallurgy. Not all considered inputs and outputs are listed in this figure for reasons of clarity

communicated PCF can also be converted into a PCF without the consideration of credits, which is also done in this paper.

Limitations of this study are that the data for the DR plant and the electric melting unit are based on metallurgical models from internal communication of thyssenkrupp Steel Europe AG (tkSE, 2020). However, technical primary data of a large scale shaft furnace direct reduction process in combination with an electric melting unit are not available. Incremental improvements for the future scenarios are not considered. Emissions from combustion processes of internal transportation and emissions from the construction phase of facilities, machines, and infrastructure of the integrated steel site are not included in this study. The cut-off criteria are conform to those defined by the Worldsteel Association [31]. Secondary data for inputs and co-products are taken from the GaBi software, database 2021.1 [32]. Further information and a list including all used GaBi databases are given in the supplementary materials of this paper.

Product Carbon Footprint for a Natural Gas-Based Direct Reduction Plant with an Integrated Electric Melting Unit

Goal and Scope

DR plants in combination with electric melting units are able to replace blast furnaces on a like for like basis. The outline of mass streams and boundaries is shown in Fig. 3 and matches Case 3 in Fig. 1, which uses a combination of electric melting and BOF technology. A carbon footprint assessment for the scenario natural gas-based (NG-Case) direct reduction with subsequently electrically melting is presented here. The inner boundary of Fig. 3 (white zone) includes the processes of the integrated site, the outer boundary (grey zone) includes the upstream materials and co-products, which are also considered within this study. The further downstream treatment of the hot-rolled coil or its use phases are excluded, since this carbon footprint

Table 1 Major inputs of the integrated steel site for the NG-Case

Input	[Unit input/ kg hot-rolled coil]
Iron ore pellets (kg)	1.5
Scrap (kg)	0.2
Natural gas (MJ)[a]	13
Electricity (MJ)	2.7
Coal (kg)	0.015

[a]Related to lower heating value (LHV) of 43.3 MJ/kg

Table 2 Life cycle inventory (LCI) results of the NG-Case following the cradle-to-gate approach

Greenhouse gas	[kg/kg hot-rolled coil]
Carbon dioxide	1.3
Methane	1.3e-3

assessment is a cradle-to-gate approach considering all processes until the product hot-rolled coil.

The product of the electric melting unit is an equal hot metal as the product from the BF. The hot metal is further refined within existing BOFs into crude steel. Thus, steel refining, secondary metallurgy, steel casting, and downstream processes do not need to change comparing a conventional integrated steel site.

The DR plant is fed exclusively with iron ore pellet feed. In general, the use of lump ore could be possible, as well. Subsequently, the DRI is charged hot into the electric melting unit. No co-product gas is generated from a DR plant. Although from the melting unit a carbon monoxide rich off-gas emerges, its amount is far below the range of the off-gases from the replaced BF. In sum, every DR plant in combination with an electric melting unit replacing a BF needs additional, newly generated electricity. Thus, the electricity surplus of the conventional BF-BOF route turns into a deficit for the DRI-based route.

Within the NG-Case, natural gas is used for the gas preheater of the DR plant and for the slab heating of the hot-rolling process, see Fig. 3. The electric melting unit and the BOF produce a carbon-monoxide rich off-gas. This could be converted into chemical products like methanol [33]. At least the process gases could be used for thermal heat supply. It is assumed that the process gases replace natural gas energetically one by one. Therefore, credit is given for the replacement of heat supply by natural gas. Since it is not sure, in which processes the off-gases will be used, the emissions, which result from incineration of the process gases, are attributed to the processes, in which the gases are produced: BOF and melting unit. The other emissions are attributed to those processes where they are emerged.

In order to keep up the useful cooperation between the steel and the cement industry, the produced slag from the electric melting unit should be able to substitute cement. It is a necessity that this slag adjustment is a goal of research activities. In this paper, it is assumed that the electric melting unit's slag has the same characteristics like the blast furnace's slag so that identical specific credit [kg CO_2eq/kg slag] is given for the co-product. The GWP without this credit is also presented.

Life Cycle Inventory

The data for the NG-Case are taken from internal communication of tkSE (2020). The cut-off criteria are conform to those defined by the Worldsteel Association [31]. Further explanation is given in the supplementary materials. The iron and energy feedstock of the integrated steel site are listed in Table 1. Other inputs like alloying elements, oxygen or fluxes (Fig. 3) are not listed in the table but considered in the carbon footprint assessment according to the defined cut-off criteria. The listed data are the most relevant for a comparison of the made scenarios.

The major energetic input is shifted from coal (Base Case, [27]) to natural gas. The scrap input is kept constant for reasons of comparability. Imported electricity is modelled as a German renewable electricity mix from the year 2018 according to the Environment Agency [34]. As renewable energy sources electricity from wind power, photovoltaics, biogas, biomass, hydropower, and geothermal energy are used. The construction of e.g., photovoltaics or windmills requires fossil energy. For the renewable energies the GHG emissions produced in the entire life cycle of the plants are considered including the construction and end-of-life phase [32].

Concerning the GHG emissions of the cradle-to-gate analysis carbon dioxide is the most significant GHG, see Table 2. Methane emissions are mainly caused by natural gas supply.

Life Cycle Impact on Climate Change

Already in this scenario, the carbon footprint of hot-rolled coil reduces remarkably to 1.4 kg CO_2eq/kg hot-rolled coil, see Fig. 4.

Since the reduction of the iron ores is shifted from coal to natural gas the direct impact of the integrated site is more than halved compared to the Base Case leading to a GWP of 0.82 kg CO_2eq/kg HRC. While in the Base Case

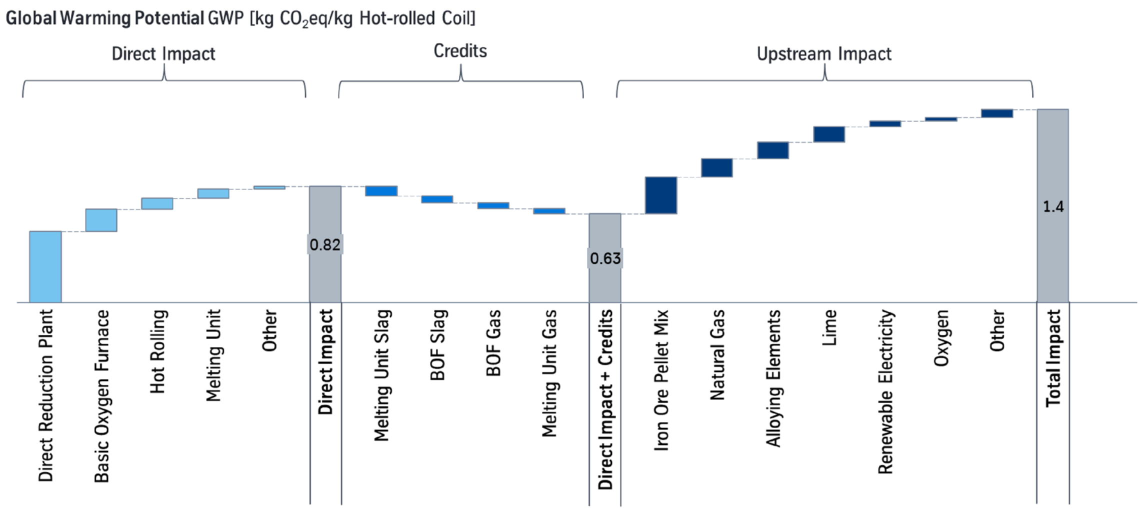


Fig. 4 Global warming potential (GWP) of hot-rolled coil, produced over a natural gas-based direct reduction with an integrated electric melting unit (NG-Case). The respective system boundaries are referred to Fig. 3. The data are derived from internal communication of tkSE, year 2018–2020

Table 3 Carbon footprint of hot-rolled coil as a function of the electricity mix

Electricity mix Input	Carbon footprint of electricity mix [kg CO_2eq/kWh]	Carbon footprint of hot-rolled coil [kg CO_2eq/kg HRC]
German renewable Mix[a]	0.056	1.4
German grid mix[b]	0.54	1.7
European grid mix[c]	0.39	1.6

The electricity mix is used for the DR plant, melting unit, BOF, casting, and natural gas-based hot-rolling.

[a]German renewable electricity mix, year 2018 according to the Environment Agency [34]; GaBi database, 2021.1: "DE: Electricity mix (energy carriers, generic)".

[b]GaBi database, 2021.1: "DE: Electricity grid mix"

cGaBi database, 2021.1: "EU-28: Electricity grid mix"

electricity created a surplus, this credit turns into a burden for electricity supply. The direct impact and the credits sum up to a GWP of 0.63 kg CO_2eq/kg HRC.

This positive effect is narrowed by an increasing upstream impact. The DR plant is exclusively fed with iron ore pellets, which production accounts for the highest part of the upstream impacts. Yet, in sum the total GWP decreases significantly compared to the Base Case. Without consideration of a credit for the slag from the melting unit and from the BOF the GWP would be 1.5 kg CO_2eq/kg HRC.

The improvement of the GWP compared to the Base Case is based on a shift from using coal for reducing and melting the iron ores towards using natural gas for reducing and renewable electricity for melting the iron ores. If no renewable electricity is used but a German or European grid mix the GWP increases up to 1.7 kg CO_2eq/kg HRC, see Table 3.

Product Carbon Footprint for a Hydrogen-Based Direct Reduction Plant with an Integrated Electric Melting Unit

Goal and Scope

DR plants allow a stepwise transition from natural gas towards hydrogen input. The potential of an only hydrogen operation is discussed in the following.

The system boundary of the H_2-Case is in accordance to the NG-Case (Fig. 3). Instead of natural gas hydrogen is used for the DR plant. It is assumed that the hydrogen is from electrolysis driven by a renewable electricity mix. No credit is given for the co-product oxygen of the electrolysis process. The gas preheater of the DR plant is electrified as well as the slab heating, see Fig. 3. The carbon content

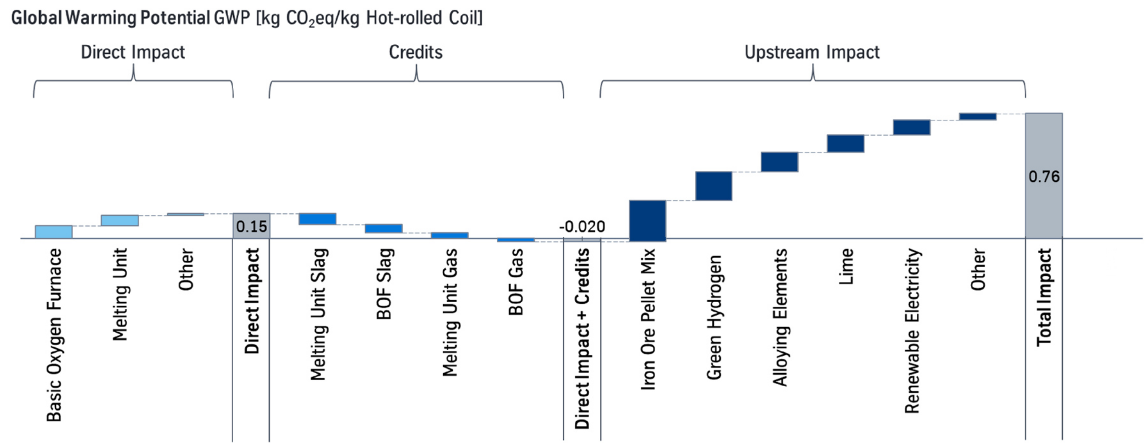


Fig. 5 Global warming potential (GWP) of hot-rolled coil, produced over a hydrogen-based direct reduction with an integrated electric melting unit (H_2-Case). The respective system boundaries are referred to Fig. 3. The data are derived from internal communication of tkSE, year 2018–2020

of the DRI would be zero when using pure hydrogen as reducing gas in the DR plant. Since in the electric melting unit the DRI should be further reduced and carburized to hot metal, coal is added in the electric melting unit. It is assumed that the C-content of the hot metal is adjusted from typically 4.5% C to 2.0% C, since the carbon input would be minimized in case of an only hydrogen reduction. The DRI is charged hot into the electric melting unit.

Likewise in the NG-Case it is assumed that the off-gases from the electric melting unit and the BOF are used for thermal heat supply and thus credits for natural gas substitution are given. In the long-term these credits may not be justified anymore and credits for renewable hydrogen supply would be rather appropriate instead. The slag from the electric melting unit is assessed as a cement substitute. With decreasing environmental impacts of the cement industry in the long-term these credits will decrease, as well. Therefore also the GWP of hot-rolled coil without consideration of credits is communicated.

Table 4 Major inputs of the integrated steel site for the H_2-Case

Input	[unit input/kg hot-rolled coil]
Iron ore pellets (kg)	1.5
Scrap (kg)	0.2
Coal (kg)	0.039
Electricity (MJ)	5.7
Hydrogen (MJ)[a]	6.9

[a]Related to LHV (120 MJ/kg)

Table 5 Life cycle inventory (LCI) results of the H_2-Case following the cradle-to-gate approach

Greenhouse gas	[kg/kg hot-rolled coil]
Carbon dioxide	0.63
Methane	3.4e-3

Life Cycle Inventory

The data for the H_2-Case are taken from internal communication of tkSE (2020). The iron and energy feedstock of the integrated steel site are listed in Table 4. The defined cut-off criteria are described in the NG-Case.

The major energetic inputs are electricity and hydrogen. Imported electricity is modelled as a German renewable electricity mix from the year 2018 according to the Environment Agency [34]. The hydrogen is assumed to be produced from the same renewable electricity mix via water electrolysis [27]. Thus, in sum 17 MJ/kg hot-rolled coil of electric energy are required. According to a GaBi database for an electrolysis process,[4] an electricity demand of 192 MJ/kg H_2 is needed, which is equivalent to an efficiency of 62.5% [lower heating value (LHV) of hydrogen/energy unit of electricity].

Concerning the GHG emissions of the cradle-to-gate analysis carbon dioxide is the most significant GHG, see Table 5. The methane emissions are mainly caused by the renewable electricity. The renewable energy input contains electricity production from biogas. Thereby fugitive methane emissions are emerged.

[4] GaBi database, 2021.1: "GLO: Hydrogen (electrolysis, decentral – for partly aggregation, open input electricity)".

Table 6 Carbon footprint of hot-rolled coil as a function of the electricity mix for the H_2-Case

Electricity mix Input	Carbon footprint of electricity mix [kg CO_2eq/kWh]	Carbon footprint of hot-rolled coil [kg CO_2eq/kg HRC]
German renewable mix[a]	0.056	0.76
German grid mix[b]	0.54	3.0
European grid mix[c]	0.39	2.3

The electricity mix is used for the water electrolysis, DR plant, melting unit, BOF, casting, and electrified hot-rolling.

[a]German renewable electricity mix, year 2018 according to the Environment Agency [34]; GaBi database, 2021.1: "DE: Electricity mix (energy carriers, generic)".

bGaBi database, 2021.1: "DE: Electricity grid mix"

cGaBi database, 2021.1: "EU-28: Electricity grid mix"

Life Cycle Impact on Climate Change

In the concluding H_2-Case the carbon footprint is further reduced to 0.76 kg CO_2eq/kg HRC, see Fig. 5.

The main impact on climate change is caused by the upstream processes, which add up to 0.78 kg CO_2eq/kg HRC. The iron ore input in form of exclusively pellets causes the highest part of the upstream processes leading to a GWP of about 0.25 kg CO_2eq/kg HRC. In addition, the alloying elements and burnt lime have a significant impact on the total GWP. Besides the material input, the imported renewable electricity mix as well as the indirectly required electricity for the hydrogen electrolysis lead to a GWP of about 0.26 kg CO_2eq/kg HRC. The hydrogen has a specific footprint of 3.06 kg CO_2eq/kg H_2 [27]. These impacts are based on data referring to a time span between year 2018 and 2020. These results demonstrate that besides the processes of an integrated steel site, also the environmental impacts of upstream processes and renewable electricity supply will need to be reduced.

Emissions from incineration of the BOF gas and the melting unit gas generate a GWP of 0.15 kg CO_2eq/kg HRC. Thus, there is still a direct impact of the integrated steel site, since it still depends on carbon. It maintains that the steel industry may rely on a biogenic carbon source in the future. The GWP without consideration of credits is 0.93 kg CO_2eq/kg HRC.

The improvement of the GWP compared to the Base Case and the NG-Case results from the fact that the iron ores are reduced with hydrogen, which results from renewable electricity, and melted with renewable electricity. If no renewable electricity is assumed but a European or German grid mix, the carbon footprint of the HRC increases up to 2.3 or 3.0 kg CO_2eq/kg HRC, see Table 6. This underlines the importance for the availability of renewable electricity.

A comparison of Tables 3 and 6 results in a break-even point of 0.21 kg CO_2eq/kWh electricity. Below this carbon footprint, the use of hydrogen from electrolysis is superior to the use of natural gas regarding to the impact on climate change.

Energy Transformation of the Steel Industry

In the following, the energy transformation of a coal-based conventional integrated steel site towards a hydrogen- and electricity-based integrated site is summarized and discussed based on the results of the life cycle inventories. In all scenarios an equal input of scrap is assumed.

Figure 6 gives a detailed overview on the changing energy demands (LHV) of the integrated steel site in subsequent steps.

(a) *Base Case* The demand of energy and reducing agents of a conventional BF-BOF route is almost exclusively provided by coal (21 MJ/kg HRC). The energy demand of natural gas is 0.43 MJ/kg HRC. The pyrolysis of coal into coke and the reduction of iron ores by coal and coke leads to process gases, which provide heat and electricity for the integrated site. Surplus electricity is even exported as part of national grids. The direct energy demand for the processes sinter plant, coke oven, blast furnace, BOF, casting, hot-rolling, and energy output from the power plant is presented (Fig. 6, pillar a). The carbon footprint of this scenario is presented in Fig. 2.

(b) The iron ores are directly reduced by natural gas in a DR plant and subsequently melted in an electric melting unit. The DRI is charged hot into the melting unit. DR plants convert integrated sites from electricity producers to electricity consumers. Small amounts of coal (0.015 kg/kg HRC) are still added in the electric melting unit to further reduce the wustite of the DRI into iron and to carbonize the iron into hot metal. The reduction of the wustite improves the FE-yield of the process chain. The direct energy demand for the processes DR plant, electric melting unit, BOF, casting,

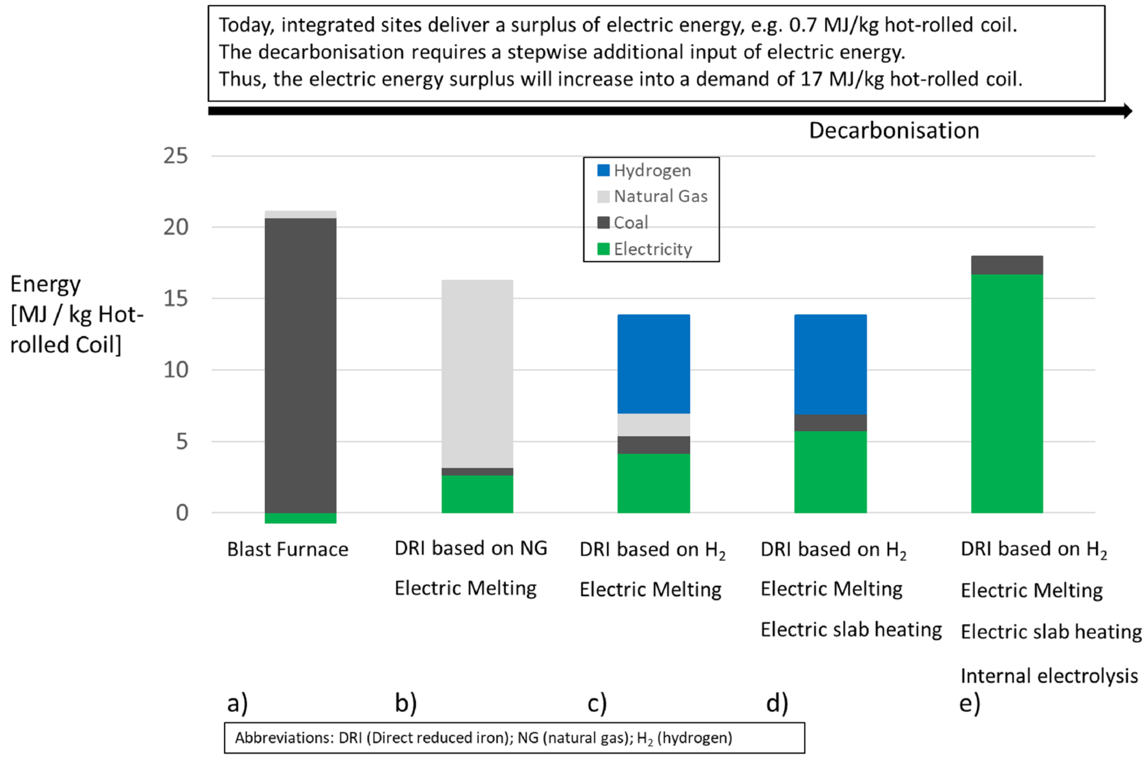


Fig. 6 Future energy demand of an integrated steel mill

and hot-rolling is presented. The carbon footprint of this scenario is presented in Fig. 4.

(c) The direct reduction is completely based on hydrogen. The preheating of the hydrogen is electrified. The DRI is also charged hot into the electric melting unit. As DRI from hydrogen reduction is carbon free, some extra carbon (0.039 kg coal/kg HRC) has to be introduced to promote beneficial metallurgical reactions. Natural gas is used for slab heating within the hot-rolling processes. The direct energy demand for the processes DR plant, electric melting unit, BOF, casting, and hot-rolling is presented.

(d) As a further step, the slab heating of the hot-rolling process is electrified. The direct energy demand for the processes DR plant, electric melting unit, BOF, casting, and hot-rolling is presented. The carbon footprint of this scenario is presented in Fig. 5.

(e) Finally the energy demand for hydrogen is translated into a need for electricity matching on-site electrolysis. A constant efficiency of 62.5% (LHV of hydrogen / electricity demand of electrolysis)[5] is assumed. The direct energy demand for the processes electrolysis, DR plant, electric melting unit, BOF, casting, and hot-rolling is presented. The carbon footprint of this scenario is the same as in d), since the carbon footprint assessment is a cradle-to-gate analysis and thus the step from electricity to hydrogen production is included.

The decrease of the energy demand from the Base Case (a) to the NG-Case (b) has several reasons:

- A blast furnace consumes about 15 MJ energy in form of coal and coke to produce one kg of hot metal. Via a DR plant combined with electrically melting, only 13 MJ are required to produce one kg of hot metal. The process gas of the DR plant is recirculated within a close loop. The blast furnace gas is used for thermal heat and is electrified, whereby in both steps energy is dissipated.
- A coke plant is needed for the operation of a blast furnace. If natural gas is used for the direct reduction, no respective upstream process is needed.
- Sinter is used as an iron feedstock within a blast furnace. The sintering process consumes energy, mainly in form of coke. About 1.6 MJ energy per kg of sinter is required. A direct reduction plant is fed with iron ore pellets or lump ore. The pelletizing process is outside the system boundaries for the energy-related consideration of Fig. 6. Anyway, the process of pelletizing is less energy-

[5] GaBi database, 2021.1: "GLO: Hydrogen (electrolysis, decentral – for partly aggregation, open input electricity)".

intensive than the sintering process and using directly lump ore instead of pellets is a possibility, as well.

For decarbonizing the steel industry the energy surplus of a conventional integrated site will increase into a demand of 17 MJ per kg of HRC, which is equal to 4.7 kWh/kg HRC. This electric energy has to be delivered by renewable energies.

Within the European Union (28) an absolute amount of 159 million tonnes of steel is produced in year 2019[6] [35]. The share of the BF-BOF route is 59% leading to about 94 million tonnes of steel produced via the BF-BOF route in EU (28) in year 2019 [35]. The transformation from the BF-BOF route towards climate-neutral steel production will most likely be performed via hydrogen-based direct reduction combined with electrically melting. This production route is from technological readiness and scalability the leading technology alternative to the primary BF-BOF route [1]. Combining nowadays European primary steel production [35] and the results from Fig. 6, a shift from present European coal-based steel production towards an electrically based steel production would lead to an electricity demand of about 440 TWh per year for the European Union (28), an immense future challenge.

Conclusions

Expected future demand of steel suggests that integrated steel mills will continue to produce steel far beyond the year 2050 from iron ore. As a pre-condition integrated sites have to become significantly CO_2eq-reduced: Coal-based reduction of ore needs to be replaced by carbon-reduced techniques. Modern DRI plants are technical ready and capable to support such a transition away from coal towards natural gas and subsequently hydrogen. Although a pure hydrogen-based shaft furnace direct reduction process in a large scale has not been realized yet the concept is technically feasible and has been proven for hydrogen-rich operation modes.

Low GHG-intensive steel production requires electrically melting of the direct reduced iron. Any use in blast furnaces or as scrap substitute in BOFs can only be a transition step. After electrically melting a pre-melt of DRI/HBI can either still pass the BOF or already be used as raw steel. The decision depends on the product portfolio—many of today's chemical steel compositions require subsequent BOF treatment.

Whereas there are plenty of LCA and PCF studies about conventional steel production via the BF route there is a lack of studies for future steel production via a DR plant and electrically melting. This study fills this gap by providing a holistic carbon footprint assessment according to ISO 14067 for steel, produced via direct reduction, electrically melting, and subsequent refining in a BOF. The carbon footprint assessments for all considered scenarios are based on the same methodologies and databases; so these have an impact on the absolute values but their sensitivity on the deltas between these scenarios is much weakened.

The actual value of traditional coal-based steel production causes a global warming potential of 2.1 kg CO_2eq/kg HRC. As a transition scenario, natural gas-based direct reduction can reduce remarkably the global warming potential to 1.4 kg CO_2eq/kg hot-rolled coil. With hydrogen-based direct reduction the carbon footprint can further be reduced to 0.76 kg CO_2eq/kg hot-rolled coil.

The most significant driver is the carbon footprint of the electricity mix, which is used for water electrolysis and directly for the processes of the integrated steel site. If no renewable electricity is available and e.g., the current European electricity mix has to be used the carbon footprint of steel can even increase compared to the BF-BOF route.

Until 2050, the energy surplus of an integrated site will increase into a demand of 17 MJ per kg of hot-rolled coil, which is equal to 4.7 kWh/kg HRC. In order to reach a fossil-free steel production, this electric energy has to be delivered by renewable energy, an immense future challenge.

Limitations of the study are that the data for the future scenarios are based on metallurgical models. If primary data are available this paper can be extended to a life cycle assessment (LCA) considering more environmental impact categories than climate change. Since the used data of this paper are confidential company data, no complete inventory data set is presented. Thus, the reproducibility is limited. Within a life cycle sustainability assessment (LCSA) also economic and social pillars could be analyzed. Concerning the assessment of co-products the methodology of system expansion is used. Credits are given in dependency of the environmental impacts of the substituted primarily produced products. For future scenarios these values have a degree of uncertainty. That's why, the results are also presented without consideration of credits. Emissions from collecting, sorting and processing of scrap are not considered in this paper. In addition, emissions from the construction phase of facilities, machines, and infrastructure of the integrated steel site are not included.

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[6] Refer to year 2019 to diminish Covid-19 effects.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Liu W, Zuo H, Wang J, Xue Q, Ren B, Yang F (2021) The production and application of hydrogen in steel industry. Int J Hydrog Energy 46(17):10548–10569. https://doi.org/10.1016/j.ijhydene.2020.12.123
2. Wang RR, Zhao YQ, Babich A, Senk D, Fan XY (2021) Hydrogen direct reduction (H-DR) in steel industry—An overview of challenges and opportunities. J Clean Prod 329:129797. https://doi.org/10.1016/j.jclepro.2021.129797
3. World Steel Association (2021) World steel in figures. https://www.worldsteel.org/en/dam/jcr:976723ed-74b3-47b4-92f6-81b6a452b86e/World%2520Steel%2520in%2520Figures%25202021.pdf. Accessed 05 July 2021
4. IEA (2020) Iron and steel technology roadmap—towards more sustainable steelmaking. https://www.iea.org/reports/iron-and-steel-technology-roadmap. Accessed 05 July 2021
5. Hasanbeigi A, Arens M, Price L (2014) Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction: a technical review. Renew Sustain Energy Rev 33:645–658. https://doi.org/10.1016/j.rser.2014.02.031
6. Schmöle P, Lüngen HB (2007) Use of pre-reduced material in the blast furnace: metallurgical, ecological and economic aspects. Stahl Eisen 127:47–54
7. MacRosty RD, Swartz CL (2007) Dynamic optimization of electric arc furnace operation. AIChE J 53(3):640–653. https://doi.org/10.1002/aic.11104
8. Murphy T (2018) Nitrogen; an intrinsic barrier for EAF steelmaking. Material Processing Institute. In: Steel Conference organised by the Iron and Steel Society of IOM3, London, UK
9. Huellen M, Schrade C, Wilhelm U, Zulhan Z (2006) EAF-based flat-steel production applying secondary metallurgical processes. In: Ironmaking Steelmaking Conference, Linz, Austria
10. ISO 14040 (2006) DIN EN ISO 14040:2006 + Amd 1:2020. Environmental management—life cycle assessment—principles and framework
11. ISO 14044 (2006) DIN EN ISO 14044:2006 + Amd 1:2017 + Amd 2:2020. Environmental management – life cycle assessment—requirements and guidelines
12. Norgate TE, Jahanshahi S, Rankin WJ (2007) Assessing the environmental impact of metal production processes. J Clean Prod 15(8–9):838–848. https://doi.org/10.1016/j.jclepro.2006.06.018
13. Burchart-Korol D (2013) Life cycle assessment of steel production in Poland: a case study. J Clean Product 54(2013):235–243. https://doi.org/10.1016/j.jclepro.2013.04.031
14. Renzulli PA, Notarnicola B, Tassielli G, Arcese G, Di Capua R (2016) Life cycle assessment of steel produced in an Italian integrated steel mill. Sustainability 8(8):719. https://doi.org/10.3390/su8080719
15. Chisalita DA, Petrescu L, Cobden P, van Dijk HE, Cormos AM, Cormos CC (2019) Assessing the environmental impact of an integrated steel mill with post-combustion CO2 capture and storage using the LCA methodology. J Clean Prod 211:1015–1025. https://doi.org/10.1016/j.jclepro.2018.11.256
16. Backes JG, Suer J, Pauliks N, Neugebauer S, Traverso M (2021) Life cycle assessment of an integrated steel mill using primary manufacturing data: actual environmental profile. Sustainability 13(6):3443. https://doi.org/10.3390/su13063443
17. Larsson M, Grip CE, Ohlsson H, Rutqvist S, Wikström JO, Ångström S (2006) Comprehensive study regarding greenhouse gas emission from iron ore based production at the integrated steel plant SSAB Tunnplåt AB. Int J Green Energy 3(2):171–183. https://doi.org/10.1080/01971520500544036
18. Barati M (2010) Energy intensity and greenhouse gases footprint of metallurgical processes: a continuous steelmaking case study. In Energy 35(9):3731–3737. https://doi.org/10.1016/j.energy.2010.05.022
19. Harada T, Tanaka H (2011) Future steelmaking model by direct reduction technologies. ISIJ Int 51(8):1301–1307. https://doi.org/10.2355/isijinternational.51.1301
20. Arens M, Worrell E, Eichhammer W, Hasanbeigi A, Zhang Q (2017) Pathways to a low-carbon iron and steel industry in the medium-term–the case of Germany. J Clean Prod 163:84–98. https://doi.org/10.1016/j.jclepro.2015.12.097
21. Sarkar S, Bhattacharya R, Roy GG, Sen PK (2017) Modeling MIDREX based process configurations for energy and emission analysis. Steel Res Int. https://doi.org/10.1002/srin.201700248
22. Fischedick M, Marzinkowski J, Winzer P, Weigel M (2014) Techno-economic evaluation of innovative steel production technologies. J Clean Prod 84:563–580. https://doi.org/10.1016/j.jclepro.2014.05.063
23. Otto A, Robinius M, Grube T, Schiebahn S, Praktiknjo A, Stolten D (2017) Power-to-steel: reducing CO_2 through the integration of renewable energy and hydrogen into the German steel industry. Energies 10(4):451. https://doi.org/10.3390/en10040451
24. Vogl V, Åhman M, Nilsson LJ (2018) Assessment of hydrogen direct reduction for fossil-free steelmaking. J Clean Prod 203:736–745. https://doi.org/10.1016/j.jclepro.2018.08.279
25. Bhaskar A, Assadi M, Nikpey Somehsaraei H (2020) Decarbonization of the iron and steel industry with direct reduction of iron ore with green hydrogen. Energies 13(3):758. https://doi.org/10.3390/en13030758
26. ISO 14067 (2019) EN ISO 14067:2019–02. Greenhouse gases—Carbon footprint of products—Requirements and guidelines for quantification
27. Suer J, Traverso M, Ahrenhold F (2021) (2021): Carbon footprint of scenarios towards climate-neutral steel according to ISO 14067. J Clean Prod. https://doi.org/10.1016/j.jclepro.2021.128588
28. Huijbregts MA, Steinmann ZJ, Elshout PM, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycl Assess 22(2):138–147. https://doi.org/10.1007/s11367-016-1246-y
29. IPCC, 2021: Climate Change (2021) The physical science basis. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M,

Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds) Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
30. World Steel Association (2011) Life cycle assessment methodology report
31. World Steel Association (2017) Life cycle inventory methodology report
32. ©Sphera Solutions GmbH (2021): Gabi Database 2021.1
33. Wich-Konrad T, Lüke W, Oles M, Deerberg G (2020) Assessment of industrial greenhouse gas reduction strategies within consistent system boundaries. Chem Ing Tech 92(10):1393–1402. https://doi.org/10.1002/cite.202000059
34. Umweltbundesamt (2019) Erneuerbare Energien in Deutschland. Daten zur Entwicklung im Jahr 2018. https://www.umweltbundesamt.de/publikationen/erneuerbare-energien-in-deutschland-2018. Accessed 05 July 2021
35. World Steel Association (2020) World steel in figures. https://www.worldsteel.org/en/dam/jcr:f7982217-cfde-4fdc-8ba0-795ed807f513/World%2520Steel%2520in%2520Figures%25202020i.pdf. Accessed 10 July 2021

2.4 Carbon footprint assessment of hydrogen and of steel produced via a direct reduction plant with an electric arc furnace (EAF)

This section presents publication IV: 'Suer, J.; Traverso, M.; Jäger, N.: Carbon Footprint Assessment of Hydrogen and Steel. Energies 2022, 15(24), 9468. https://doi.org/10.3390/en15249468.'
As mentioned previously, the majority of European steel producers have declared DR plants as the key technology for their transformation paths. In this publication the DRI is directly processed in an EAF to crude steel. Additionally, a literature overview on the impact of different hydrogen production technologies on climate change is presented. Particular attention is given to hydrogen production from electrolysis with focus on the related electricity mix. A key result is the relationship between the carbon footprint of steel, produced via a hydrogen-based DR route, and the carbon footprint of electricity mix, which is used during the steel production route and for hydrogen electrolysis. Another focus is the comparison of a natural gas-based and a hydrogen-based DR process from a climate change perspective. The hydrogen is produced from electrolysis, driven by national and European electricity mixes considering development scenarios until 2040.

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Article

Carbon Footprint Assessment of Hydrogen and Steel

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Abstract: Hydrogen has the potential to decarbonize a variety of energy-intensive sectors, including steel production. Using the life cycle assessment (LCA) methodology, the state of the art is given for current hydrogen production with a focus on the hydrogen carbon footprint. Beside the state of the art, the outlook on different European scenarios up to the year 2040 is presented. A case study of the transformation of steel production from coal-based towards hydrogen- and electricity-based metallurgy is presented. Direct reduction plants with integrated electric arc furnaces enable steel production, which is almost exclusively based on hydrogen and electricity or rather on electricity alone, if hydrogen stems from electrolysis. Thus, an integrated steel site has a demand of 4.9 kWh of electric energy per kilogram of steel. The carbon footprint of steel considering a European sustainable development scenario concerning the electricity mix is 0.75 kg CO_2eq/kg steel in 2040. From a novel perspective, a break-even analysis is given comparing the use of natural gas and hydrogen using different electricity mixes. The results concerning hydrogen production presented in this paper can also be transferred to application fields other than steel.

Keywords: carbon footprint assessment; power production; hydrogen; direct reduction plant; electric arc furnace

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1. Introduction

In order to prevent irreversible damage, global warming has to be kept well below 2 °C, preferably below 1.5 °C [1]. Therefore, the European Commission (EC) has set an ambitious target to reduce greenhouse gas emissions by at least 55%, compared with 1990 levels, by the year 2030, and to achieve net zero emissions before the year 2050 [2]. The German Federal Constitutional Court stated that the national emission reduction targets have to be specified from the year 2031 onwards, to substantiate the path between 2031 and 2050 [3].

The energy-intensive steel industry is responsible for about 7% of the global anthropogenic carbon dioxide emissions but also accounts for almost 3.5% of global gross domestic product (GDP) and 3% of global employment within combined activities [4,5]. Nevertheless, the steel industry has to make an important contribution to achieve the ambitious climate goals. Since steel is firmly established in the human way of life and also serves as a key material to enable technological climate-neutral solutions, a European scenario without steel production is not an option to solve the problem.

Steel is produced primarily with natural iron ores and secondarily with scrap recycling. About 70% of the steel production is primarily produced, mainly using the blast furnace–basic oxygen furnace (BF-BOF) route. About 30% of steel is produced secondarily, using the scrap-based electric arc furnace (EAF) route [4]. Despite efficiency gains, global carbon dioxide emissions are still increasing due to growing steel consumption and demand [6]. The increasing demand is also the reason why even in the year 2050, only about 44% of the steel demand will be able to be covered by the scrap-based EAF recycling route [7]. In consequence, breakthrough technologies in the primary steel production route are necessary.

In order to fulfil a sustainable transformation, it has to be ensured that environmental impacts are not just shifted from one process to another but a global benefit is reached. Life cycle assessment (LCA) according to ISO 14040 [8] and 14044 [9] is an established and standardized methodology used to determine the environmental impacts of a product along its life cycle. This includes the entire process chain from raw material extraction to supply, product manufacturing, use, recycling, and the disposal of waste, otherwise known as the cradle-to-grave approach. In LCA, several environmental impact categories can be considered. If, however, the focus lies on the sole impact category of climate change, it is referred to as product carbon footprint (PCF) assessment according to ISO 14067 [10]. ISO norm 14067 is in accordance with the LCA standards. Since the focus of this paper lies on the contribution to climate change of steel, the presented results are based on the methodology of ISO 14067.

The carbon footprint of steel produced using an average German BF-BOF route is roughly 2.0 kg CO_2eq/kg steel (according to GaBi database 2021.1: "DE:BF Steel billet/slab/bloom" (CML 2001-16)) (see Figure 1) [11]. This impact can be divided into individual contributions of the steel manufacturing processes, the upstream supply chain, and credits for co-products, as is shown in the carbon footprint assessment of an integrated steel site in a previous work [12]. Direct impacts of an integrated steel site include its typical processes: sinter plant, coke plant, blast furnace, BOF, steel casting, and power plant. An integrated site commonly produces co-products such as blast furnace slag, BOF slag, electricity from power plants, and co-products originating from the coke plant, which are, e.g., tar, benzene, and sulphur. These co-products replace primary production in other industries and ultimately avoid emissions. According to the principle of system expansion [9], credits are given for these co-products.

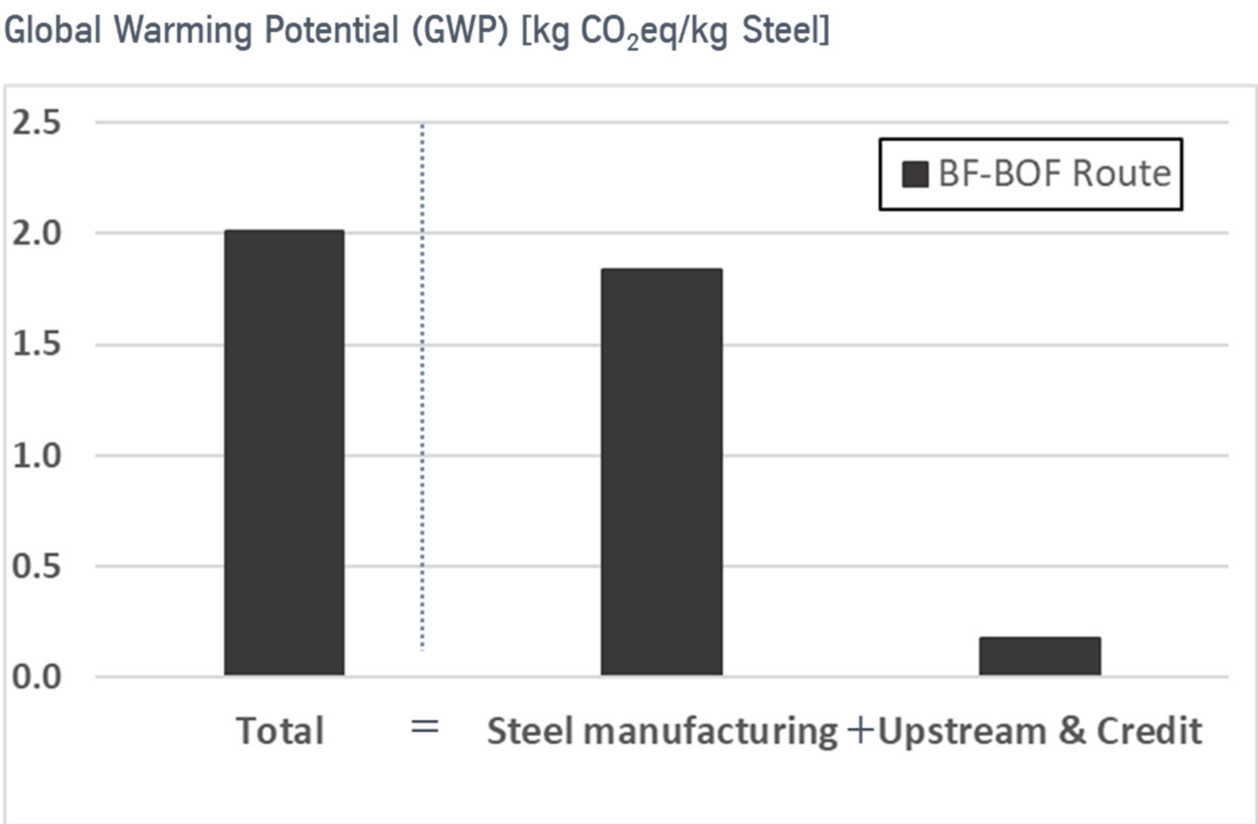

Figure 1. Global warming potential (GWP) of steel produced via the blast furnace–basic oxygen furnace (BF-BOF) route. Total GWP according to GaBi database 2021.1.

In order to reduce the greenhouse gas emissions (GHGs) of the BF-BOF route, a shift from solid primary energy sources as reducing agents is required. The BF-BOF route is based on fossil coal. Beside carbon, hydrogen is able to reduce the iron oxides. In direct reduction units, iron oxides can be reduced to direct reduced iron (DRI) by natural gas and hydrogen, respectively. Direct reduction (DR) units are technically mature and can compete with blast furnaces concerning product capacities, with the limitation that the products are different in terms of physical state and composition. The final product of a blast furnace is liquid hot metal, while the product of a DR plant is a solid reduced iron pellet that also contains some gangue. Therefore, an additional plant is required to melt DRI and to remove gangue. This can be conducted electrically in an electric arc furnace (EAF), after which liquid steel can be directly cast into slabs. If high-quality steel is required, additional processing in the so-called secondary metallurgy is necessary.

The DR technology is fully developed and commercially available [13–16]. Presently, DR plants with capacities exceeding 2.5 million tons per year are the state of the art [13,15]. Nowadays, DRI is typically reduced using gases such as natural gas or gases from coal gasification. The use of off-gases from an integrated site, such as coke oven gas or BOF off-gas, is also an alternative [17]. Using pure hydrogen, reduction in the DR plant can be completely shifted away from carbon. It has to be emphasized that for climate-neutral steel production, the production process of the hydrogen used in the DR plant, as well as the electricity used for melting, also has to be taken into account, to avoid a shift in emissions.

Nowadays, the majority of pure hydrogen is produced via steam reforming out of natural gas or gasified coal and is often referred to as grey hydrogen (the chosen colour code in this paper is based on the one of the Federal Ministry of Education and Research) [18,19]. Grey hydrogen-based steel production still requires fossil fuels. Alternatively, hydrogen can be produced through steam reforming with subsequent storage of carbon dioxide, called blue hydrogen. Another hydrogen production pathway is electrolysis. If the electricity for the electrolysis process is from renewable sources, hydrogen production does not rely on fossil fuels; therefore, it is called green hydrogen. If fossil fuels are used for the respective production of electricity, hydrogen is also defined as grey hydrogen.

Regarding the use of renewable energies, some points need to be discussed. Although all industries, as well as private consumers, require renewable electricity to achieve the overall targets, the availability of renewable energy is currently limited in Europe (EU). Additionality in the use of renewable energy has to be guaranteed, so that its use makes an impact. Additionality of a renewable energy unit can only be given if it is not receiving any offtake subsidies aimed at the power market, amongst other criteria [20]. However, as long as the share of the overall European renewable electricity mix is limited, the European targets cannot be reached. So, most of all, supply has to increase. Steel production is a continuous process, so hydrogen and electricity supply also needs to be one. For the exclusive use of renewable energy, storage capacities are required.

In a technical study by Hölling et al., CO_2-free steel production on the basis of off-shore wind energy is investigated [21]. Electricity from wind energy is used for near-site hydrogen electrolysis. The DRI and steel from an EAF are either produced onsite or different transport scenarios are investigated. For CO_2-free steel production, the costs for steel production under the most optimal conditions are increased by 350 EUR/t steel, which is equivalent to a carbon dioxide abatement cost of about 200 EUR/t CO_2. These costs are far above the steel producer’s usual margin of profit so this transformation does not go without appropriate advancement programs [21]. The development of renewable energy, the build-up of storage capacities, and the development of a hydrogen infrastructure are challenges to be addressed by the whole society and cannot be realized by the steel industry alone. That is the reason why the focus of this paper is on considering power supply with a grid mix.

More in detail, this paper aims to assess the carbon footprint of steel produced via a direct reduction unit and an EAF, whereby direct reduction with natural gas and that with hydrogen are compared to each other. A cradle-to-gate approach is used, including the production of raw materials to the production of steel. The sensitivity of hydrogen production to the respective carbon footprint of steel is investigated. To determine the state of the art, a literature overview about today's hydrogen carbon footprint is presented, considering grey, blue, and green hydrogen. Special attention is given to hydrogen from electrolysis, for which electricity is taken from a national or European grid mix. The carbon footprint is assessed by modelling an electricity mix in combination with the electrolysis process. Moreover, an outlook until the year 2040 is presented, considering both the development of electricity grid mixes and of the efficiency of the electrolysis process.

The results concerning hydrogen production gained from this paper can also be used for technical applications in fields other than steelmaking.

2. Hydrogen Production

2.1. State of the Art

Today, hydrogen production mainly relies on fossil fuels. Only 0.5% of the global hydrogen production is from renewable sources, the so-called green hydrogen. Around 6% of global natural gas consumption and 2% of global coal consumption are used for hydrogen production. As a consequence, hydrogen production causes about 830 million tons of CO_2 emissions per year. This corresponds to 2.5% of global CO_2 emissions [19]. If a hydrogen production rate of about 70 Mt per year is taken into account, this leads to about 12 kg CO_2/kg H_2.

A literature overview on the impact of different hydrogen production technologies on climate change is given in Table 1. Not every study listed is a comprehensive carbon footprint assessment including all environmental impacts of raw material and energy supply. Therefore, a comment on the system boundary is given by the authors of this paper. The considered time span reaches from 2011 to 2025.

Grey hydrogen from natural gas-based steam reforming causes global warming potential (GWP) values between 11 and 13 kg CO_2eq/kg H_2 [11,22–26]. This is in line with the global average hydrogen-related carbon dioxide emissions. In the presented studies, different system boundaries and assumptions are considered. Nevertheless, the direct impact of the steam reforming process is the major contributor across all listed studies. The impact of natural gas production and transport is 1.7 kg CO_2eq/kg H_2, based on a calculation from GaBi databases in 2021.

Grey hydrogen from coal gasification causes GWP values between 19 and 24 kg CO_2eq/kg H_2 in the reviewed literature [25,27,28].

The carbon footprint of grey hydrogen from electrolysis driven by a fossil-based electricity mix varies between 1.1 and 35 kg CO_2eq/kg H_2 [25,26,29]. In the case of low-carbon electricity mixes, with high shares of renewable or nuclear energy, the carbon footprint is relatively low, whereas for coal-, oil-, and natural gas-based electricity, the footprint is relatively high.

According to the results of the literature review, blue hydrogen from steam reforming with carbon capture and storage (CCS) of carbon dioxide causes GWP values between 0.60 and 4.7 kg CO_2eq/kg H_2 [24,26,29]. Here, the carbon footprint depends significantly on the electricity mix that is required for CO_2 capture. Howarth and Jacobson describe the PCF of blue hydrogen to be between 11 and 22 kg CO_2eq/kg H_2. Their research focuses on fugitive methane emissions and presents the results of the GWP considering time frames of 20 years and 100 years [30]. Since methane is a very strong but, in comparison with CO_2, not very durable GHG, the considered time frame has a significant impact on the GWP of methane. The fugitive methane emissions are assumed to be 3.5% of natural gas input. This high value explains the high carbon footprint of blue hydrogen in the study [30].

Green hydrogen from electrolysis driven by renewable electricity has a carbon footprint between 1.0 and 5.1 kg CO_2eq/kg H_2 [22,23,25]. The footprint mostly depends on the renewable electricity technology, as well as the efficiency of the electrolysis process.

Table 1. Global warming potential (GWP) of different hydrogen production technologies.

Technology	GWP	Year of Data	Source	Comment on System Boundary
	kg CO_2eq/kg H_2			
Grey hydrogen from reforming process				
SMR [a]	11.1	2021	[11]	LCA [b] analysis according to GaBi database "DE: Hydrogen (steam reforming natural gas)"
SMR	12.0	2011	[22]	LCA of hydrogen production
SMR	11.9	2012	[23]	LCA of hydrogen production
SMR	13.0	2017	[24]	Holistic techno-environmental analysis
SMR	12.1	2018	[25]	LCA of hydrogen production
ATR [c]	13.3	2025	[26]	Includes natural gas production and transport
CG [d]	22.7	2018	[27]	Holistic approach
CG	24.2	2018	[25]	LCA of hydrogen production
CG	19.0	2020	[28]	Only directly related CO_2 emissions; no upstream
Grey hydrogen from electrolysis driven by fossil-based electricity				
	35.0	2015	[29]	Carbon footprint analysis; grid mix Netherlands 2015
	1.13	2015	[29]	Carbon footprint analysis; grid mix Norway 2015
PEM [e]	29.5	2018	[25]	LCA of hydrogen production
SOEC [f]	23.3	2018	[25]	LCA of hydrogen production
	10.0	2025	[26]	Grid mix Germany 2025; stated policy scenario
	12.0	2025	[26]	Grid mix Germany 2025; failed policy scenario
Blue hydrogen from reforming with carbon capture and storage				
ATR	0.64	2016	[29]	Carbon footprint analysis
SMR	1.73	2015	[29]	Carbon footprint analysis; grid mix Netherlands 2015
ATR	2.55	2015	[29]	Carbon footprint analysis; grid mix Netherlands 2015
SMR	3.40	2017	[24]	Holistic techno-environmental analysis
SMR	1.14	2018	[29]	Carbon footprint analysis; grid mix Norway 2015
ATR	0.82	2018	[29]	Carbon footprint analysis; grid mix Norway 2015
SMR	11–22	2021	[30]	Carbon footprint analysis; focus on fugitive methane emissions
ATR	4.67	2025	[26]	Includes natural gas production and transport
Green hydrogen from electrolysis driven by renewable electricity				
PEM	2.21	2018	[25]	LCA of hydrogen production
Solar	2.00	2011	[22]	LCA of hydrogen production
Wind	1.2	2011	[22]	LCA of hydrogen production
Solar	2.4	2012	[23]	LCA of hydrogen production
Wind	0.97	2012	[23]	LCA of hydrogen production
Wind; SOEC	5.10	2018	[25]	LCA of hydrogen production

[a] SMR (steam methane reforming); [b] LCA (life cycle assessment); [c] ATR (autothermal reforming); [d] CG (coal gasification); [e] PEM (proton exchange membrane); [f] SOEC (solid oxide electrolysis cell).

The storage and transportation of hydrogen is challenging in a few aspects, which are summarized in a review paper by Dawood et al. (2019) [31]. Hydrogen is able to escape through materials due to its small molecular size. This can lead to hydrogen embrittlement, which can weaken the materials and lead to destruction. Once released, hydrogen generally dissipates rapidly due to its low density. However, it becomes a safety concern if the gas accumulates and builds an explosive mixture in combination with oxygen. Since the hydrogen market is experiencing a ramp-up, it is believed that hydrogen technology will become as safe as other fuels that are in use today [31,32].

The focus of this paper lies on hydrogen from electrolysis operated with a grid mix. State-of-the-art grid mixes for Poland, France, Germany, and Europe (EU-28) are modelled. Additionally, the expected grid mixes for Germany and Europe are modelled for the years 2030 and 2040. Furthermore, a forecast is provided for the efficiency of the electrolysis process. The goal is to reveal the environmental impact of hydrogen production on the related hydrogen-based steel production.

2.2. Carbon Footprint of Hydrogen from Electrolysis

In the following section, the carbon footprint assessment of hydrogen, produced via water electrolysis, is presented for different electricity grid mixes.

2.2.1. Goal and Scope

The declared unit is 1 kg of hydrogen. The related system boundaries, as well as the sources for the electricity grid mix, are highlighted in Figure 2.

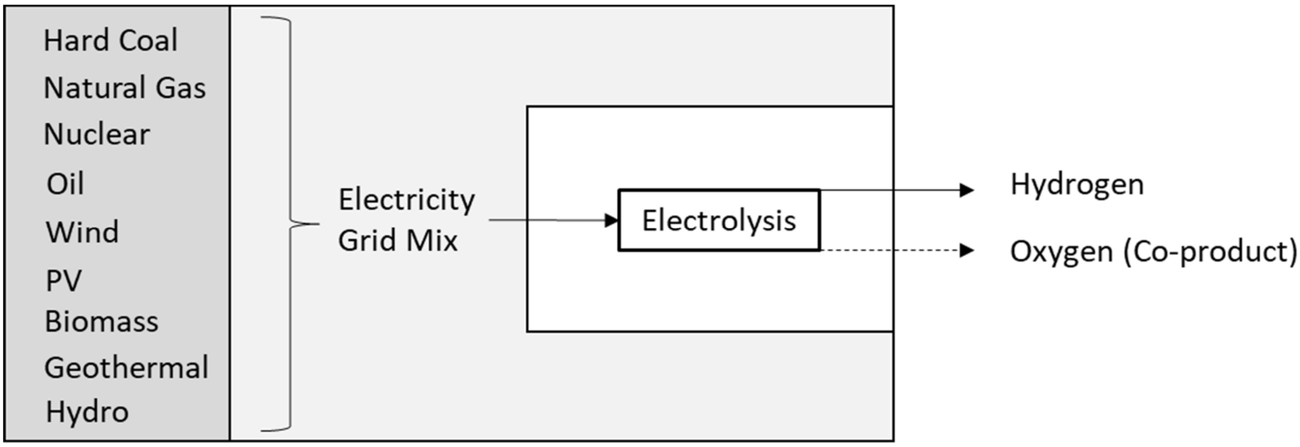

Figure 2. System boundary for hydrogen production.

This study is conducted using a cradle-to-gate approach. All impacts on climate change of raw material supply, transport, and manufacturing are considered [9].

Beside hydrogen, oxygen is produced as a co-product during the electrolysis process. Co-products can be evaluated with the methodology of system expansion, in which credits are given if they replace primary production in other industries [9]. However, in hydrogen transformation, it is not guaranteed that the co-product, oxygen, is to be used completely. Thus, the results are presented without any credit for the co-product.

2.2.2. Life Cycle Inventory

Hydrogen is modelled by combining the electrolysis process of "GLO: Hydrogen (electrolysis, decentral—for partly aggregation, open input electricity)" from GaBi database 2021.1 with different electricity mixes [11]. The life cycle inventory (LCI) value of hydrogen can be calculated by adding up the LCI value related to the required electricity grid mix to the LCI value related to the electrolysis process. For the example of carbon dioxide, the calculation is presented in Equation (1).

$$LCI_{hydrogen}[kg\ CO_2/kg\ H_2] = LCI_{Electricity,Mix}[kg\ CO_2/MJ\ electricity] \cdot LHV_{H_2}/\eta_{electrolysis}[MJ\ electricity/kg\ H_2] + LCI_{Electrolysis}[kg\ CO_2/kg\ H_2] \quad (1)$$

where LHV_{H_2} refers to the lower heating value of hydrogen (120 MJ/kg) and $\eta_{Electrolysis}$ is the efficiency of the electrolysis process (MJ H_2/MJ electricity).

The electricity mixes are modelled using GaBi database "EU-28: Electricity mix (energy carriers, generic)". This database enables the creation of a generic electricity mix by varying the electricity inputs from chosen sources, such as coal, nuclear, wind, etc. The composition of the specific electricity mixes are taken from the International Energy Agency (IEA) [33] for the current national and European electricity mixes. The European forecast scenarios are taken from World Energy Outlook (2020), conducted by the IEA [34]. The German outlook scenarios are taken from Prognos et al. (2020) [35].

The data of the efficiency of the electrolysis process are taken from Prognos (2020) [36]. Beside the current efficiency, this study also provides a future outlook up to the year 2040. The average efficiency of the proton exchange membrane electrolysis (PEMEL) and the high-temperature electrolysis (HTEL) technology would increase from 60.9% (related to the lower heating value—LHV) for the year 2020 to 63.4% for the year 2040 [36] (see Table 2).

Table 2. Efficiency of electrolysis process based on Prognos (2020) [36].

Year	Efficiency $\eta_{electrolysis}$ (%) Related to LHV [a] of Hydrogen	Electricity Input (MJ/kg H_2)
2018	60.9	197
2030	62.2	193
2040	63.4	189

[a] Lower heating value.

In Table 3, the GHG emissions for hydrogen produced via a German grid mix are presented for the year 2018. The emissions are calculated using Equation (1). The contribution of the listed emissions to climate change is more than 99%.

Table 3. Greenhouse gas (GHG) emissions of German grid mix, year 2018, and respective GHG emissions for hydrogen from electrolysis.

GHG Emissions	(kg/kWh Electricity)	(kg/kg Hydrogen)
Carbon dioxide	0.44	24
Methane	1.1×10^{-3}	0.058
Nitrous oxide	1.4×10^{-5}	7.8×10^{-4}

Concerning the German electricity grid mix, carbon dioxide is the most significant GHG. Methane is mainly caused by electricity generated from hard coal, as methane is emitted during the coal mining process.

2.2.3. Carbon Footprint Results

In this paper, the characterization factors related to GWP 100 are used in order to calculate the impact on climate change for a time horizon of 100 years [10]. The global warming potential of hydrogen can be calculated with the following equation, which is in line with Equation (1):

$$GWP_{hydrogen}[kg\ CO_2eq/kg\ H_2] = GWP_{Electricity,Mix} * LHV_{H_2} / \eta_{electrolysis} + GWP_{Electrolysis} \quad (2)$$

The GWP of the electrolysis process is 0.047 kg CO_2eq/kg hydrogen (according to GaBi database 2021.l: “electrolysis, decentral—for partly aggregation, open input electricity”). This value is very low compared with the impact generated by electricity.

In this article, different national grid mixes as well as the European grid mix are compared with each other to visualize the impact of different grid mixes on the produced hydrogen (see Figure 3). Individual data points for grey, blue, and green hydrogen correspond to the values of the GWP listed in Table 1. The dotted grey line marks the average global direct impact of hydrogen production.

For three of the four considered electricity grid mixes, the resulting hydrogen carbon footprint is higher than the footprint of natural gas-based steam reforming hydrogen production (grey H_2; the three upper points result from coal-based steam reforming) and thus ultimately less favourable from a climate change perspective than the direct use of natural gas in the processes.

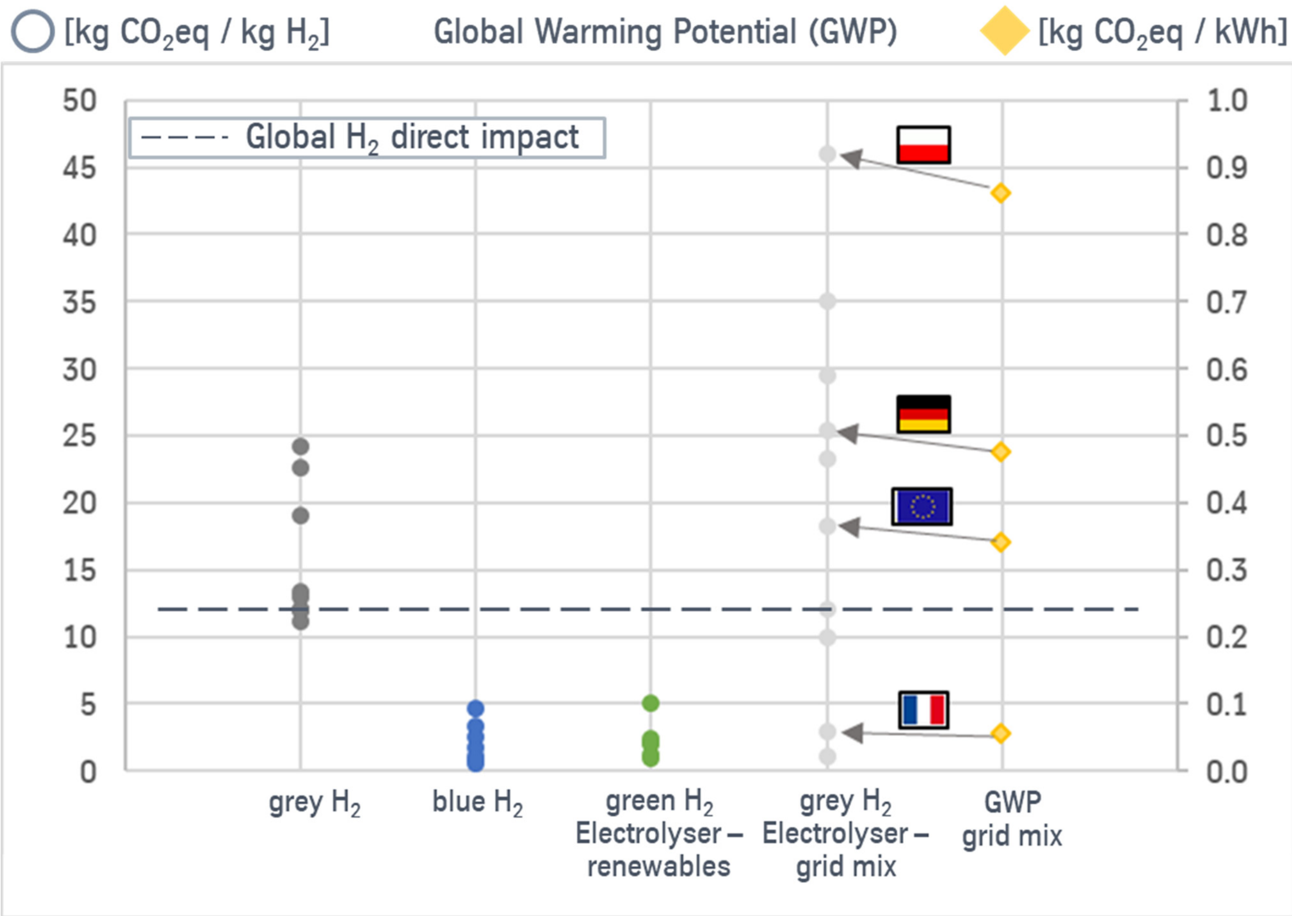

Figure 3. Impact of the electricity grid mixes on the related hydrogen carbon footprint for the nations of Poland, Germany, and France, and the European Union. The points for grey H_2 (from steam reforming), blue H_2 (steam reforming with carbon capture and storage), green H_2 (electrolysis using renewable energy), and grey H_2 electrolyser (electrolysis using fossil-based electricity) correspond to the values listed in Table 1.

2.2.4. Future Outlook (2030–2040)

In the following paragraph, an outlook on the future for the years 2030 and 2040 is given. The development of the hydrogen carbon footprint depending on the prognosis of the electricity mix and the efficiency of the electrolysis process (Table 2) is shown in Figure 4 for Europe and Germany. The results are listed next to the carbon footprint values found in the literature (Table 1). The lower blue line highlights the benchmark of the hydrogen carbon footprint. Below this line, the same amount of energy can be obtained with hydrogen, instead of natural gas, while resulting in a lower carbon footprint. The upper grey line marks the average worldwide direct impact of hydrogen production. For the European development, a stated policy scenario (a) and a sustainable development scenario (b) are considered, based on the IEA [34]. The German development scenario is based on Prognos et al. [35].

It is shown that, by 2030, the use of hydrogen is expected to result in lower impacts to the GWP than the use of natural gas.

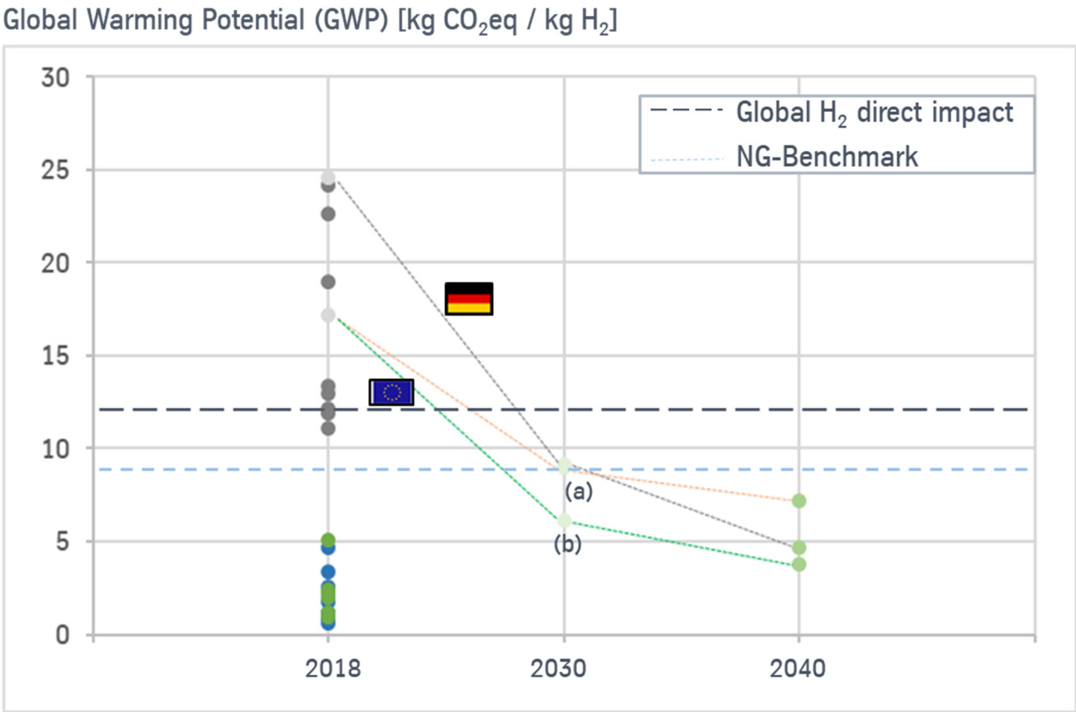

Figure 4. Development of the carbon footprint of hydrogen. For the European development, a stated policy scenario (a) and a sustainable development scenario (b) are considered, based on the IEA [34]. The German development scenario is based on Prognos et al. [35]. For the year 2018, the GWP values from the literature cited in Table 1 are listed referring to the defined colour code.

3. Carbon Footprint of Steel Produced Using a Natural Gas-Based Direct Reduction Plant and an Electric Arc Furnace

Steel production using direct reduction (DR) plants and electric arc furnaces (EAFs) allows a shift in production away from coal towards natural gas and hydrogen. From a climate change perspective, it is shown that the use of natural gas can be superior to the use of hydrogen, especially in the coming years (before 2030). In the following section, the carbon footprint assessment of natural gas-based steel production is presented. This serves as the benchmark for hydrogen-based steel production, which is presented afterwards.

3.1. Goal and Scope

The goal is to present the carbon footprint of steel (cradle to gate) produced using natural gas-based direct reduction with subsequent melting in an electric arc furnace (EAF) (see Figure 5). The steel manufacturing processes include a DR plant and an EAF as well as steel casting (Figure 5, white area). The processes of the mining, manufacturing, and transport of the required feedstock are categorized as upstream processes (grey area). Both the manufacturing and upstream processes are considered in this study.

The direct reduction unit is modelled in this study. As a baseline, natural gas is used in the direct reduction process as the reducing agent. As an alternative reducing agent, hydrogen can replace natural gas.

For the EAF process, GaBi database "DE: EAF Steel billet/slab/bloom" is used. This process references the scrap-recycling EAF process. Consequently, all environmental impacts from raw material supply, transport, and manufacturing until the product of steel is obtained (cradle-to-gate) are included, without considering the environmental impact of the scrap. In this work, the same process is used for the DRI input. No scrap input is assumed. The results presented follow the recycled content methodology, so no credits are given for end-of-life scrap [37]. Compared with the environmental impact of the whole process chain, the differences between a scrap-based EAF operation and a DRI-based EAF operation are of minor importance, as highlighted in internal studies. In addition, the focus of this article is on comparisons between different direct reduction–EAF (DR-EAF) scenarios. Since, in all DR-EAF routes, the same assumptions are made, the sensitivity to the differences between these scenarios is hardly influenced by this uncertainty of measurement.

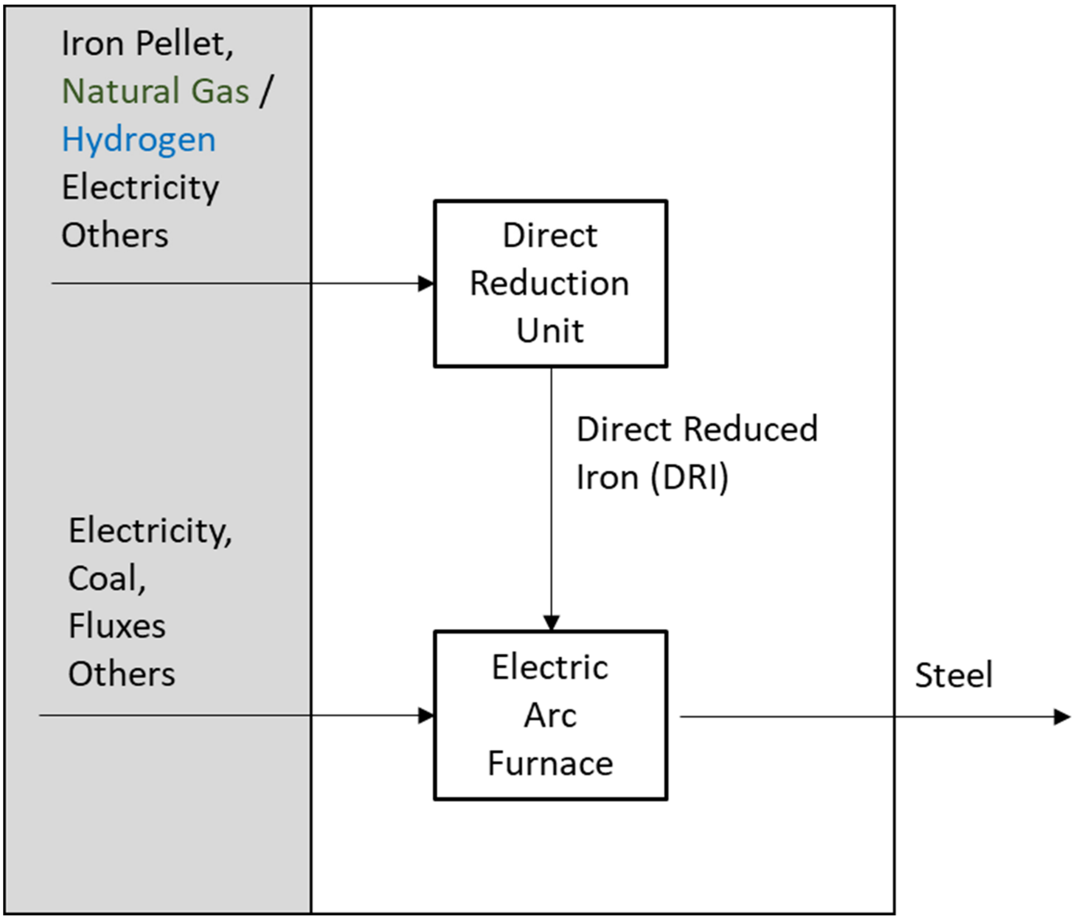

Figure 5. Steel production over the DR-EAF route. The steel manufacturing processes are listed in the white area and the inputs for these processes in the grey area. The environmental impacts of both are considered in this paper according to a cradle-to-gate approach. Either natural gas or hydrogen is used as reducing agent. Hydrogen is assumed to be obtained using electrolysis (see Figure 2).

3.2. Life Cycle Inventory

The data for the direct reduction process are based on internal communication. The data for the natural gas-based operation are in line with the ones presented by Duarte et al. (2008) and Sarkar et al. (2017) [17,38]. The electric energy demand of the EAF depends on the charging temperature, the carbon content, and the grade of metallization of DRI, amongst others [39,40]. The electric energy demand of the EAF is estimated at 500 kWh/t steel. In this scenario, a German electricity mix of the year 2018 is assumed.

Considering the DR process, at least 99% of relevant mass, energy, and environmental input and output flows are considered. Regarding the EAF process, at least 95% of mass and energy and 98% of their environmental relevance are considered according to the GaBi database [11].

The major materials and energy feedstocks of natural gas-based steel production using a DR plant and an EAF are presented in Table 4. Other inputs, such as oxygen, nitrogen, coal, and fluxes (Figure 5), are not listed in the table but are considered in the carbon footprint assessment according to the defined cut-off criteria. The listed data are the most relevant to the comparison of the assessed scenarios.

Table 4. Major inputs of natural gas-based DR plant and EAF.

Input	(Unit Input/kg Steel)
Iron ore (kg)	1.5
Natural gas (MJ)	12
Electricity (MJ)	2.2

The emissions of the life cycle inventory (LCI) are presented in Table 5. The contribution of the listed emissions to climate change is at least 99%.

Table 5. GHG emissions of steel production using natural gas-based DR plant and EAF.

GHG Emission	(kg Output/kg Steel)
Carbon dioxide	1.3
Methane	0.0021

The main contributor to climate change is carbon dioxide. Methane emissions are mainly caused by the natural gas supply for the DR plant. In addition, methane is emitted during coal mining, which is required for the coal-based electricity supply.

3.3. Carbon Footprint Results

The carbon footprint of primary steel produced with natural gas-based direct reduction with subsequent use in an electric arc furnace (NG-DR-EAF route) can be reduced to 1.4 kg CO_2eq/kg steel, as is highlighted in Figure 6.

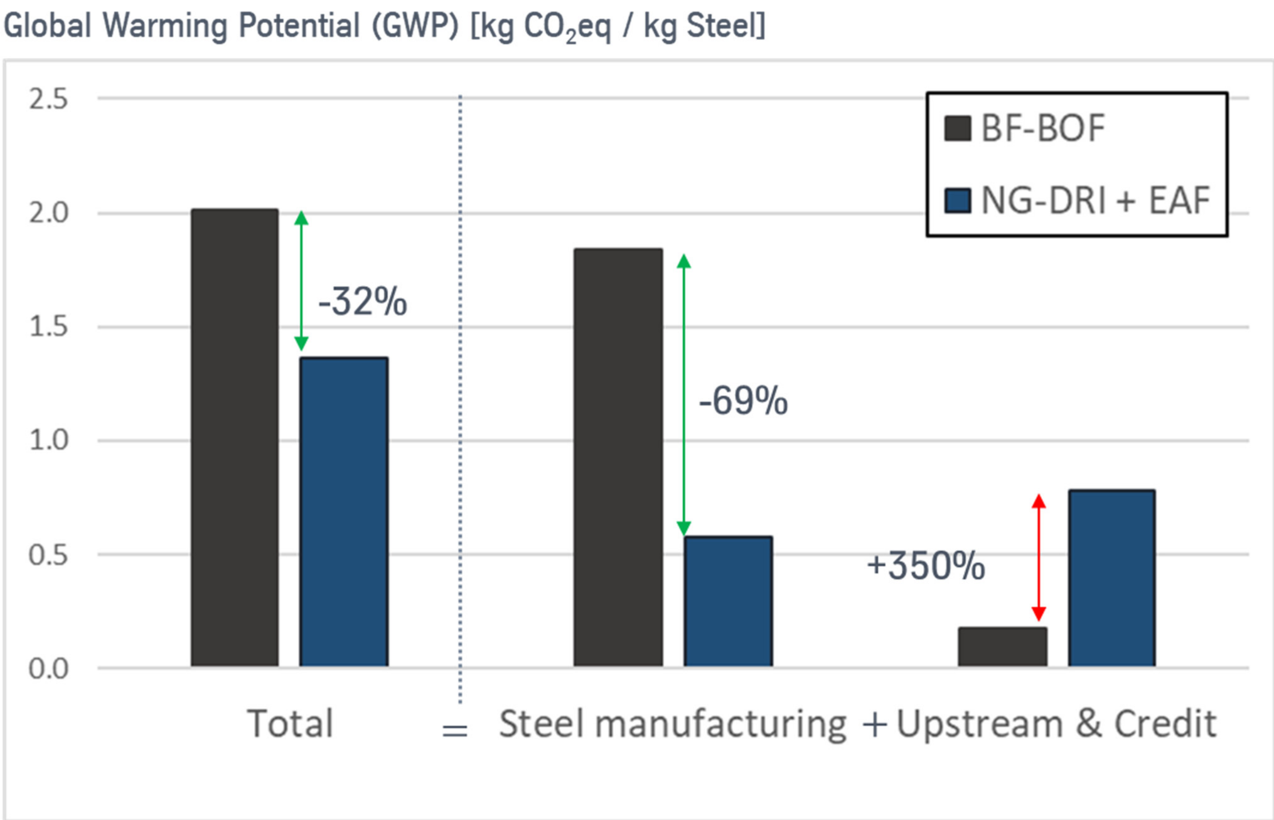

Figure 6. Global warming potential (GWP) of steel. Comparison of production using the blast furnace-basic oxygen furnace (BF-BOF) route with production using the direct reduction-electric arc furnace (DR-EAF) route.

Compared with the carbon footprint of primary steel produced using the conventional state-of-the-art BF-BOF route of 2.0 kg CO_2eq/kg steel (Figure 1), a reduction potential of 32% can be achieved. Part of the impact on climate change is shifted from the steel manufacturing processes to upstream processes. The categorization is in line with Figure 5.

E.g., in the BF-BOF route, a surplus of electricity is generated, which can be exported into the grid mix, resulting in credits. In contrast, the DR-EAF route consumes electricity. This reduces the manufacturing impact of the DR-EAF route, but part of this impact shifts to electricity production. In addition, in the DR-EAF route, less valuable co-products are produced in comparison to the BF-BOF route. In the blast furnace process, slag is produced, which serves as a high-quality cement substitute. The slag from the EAF process does not have the same quality and has limited utilization paths. Nevertheless, the total impact of steel on climate change is significantly reduced.

The major impact of the DR-EAF-route-produced steel carbon footprint originates from the production of DRI, which is 0.98 kg CO_2eq/kg steel (see Figure 7).

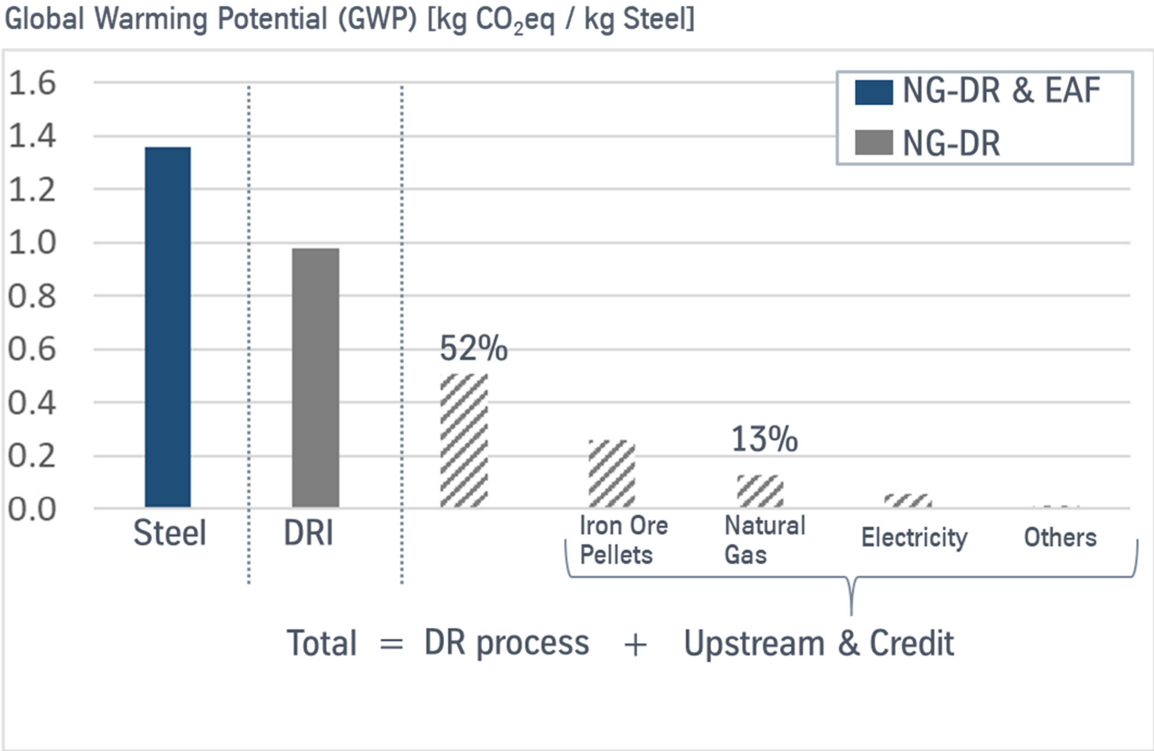

Figure 7. Carbon footprint of steel and impact of natural gas (NG)-based direct reduced iron (DRI) production.

The results demonstrate that the impact on climate change generated by GHG emissions of natural gas-based direct reduction and the respective upstream emissions of the natural gas supply add up to 65% of the DRI carbon footprint. Consequently, the substitution of natural gas with hydrogen from electrolysis could present a possibility to reduce the DRI carbon footprint, thus lowering the steel carbon footprint. Therefore, the following section focuses on production with hydrogen.

4. Carbon Footprint of Steel Produced Using a H_2-Based Direct Reduction Plant and an Electric Arc Furnace

The next step for the decarbonization of the steel industry is a shift from natural gas towards hydrogen from electrolysis. Therefore, hydrogen production as well as the required electricity for production have to be taken into account. The impact of the electricity sources on the respective carbon footprints of DRI and steel is presented in the following paragraphs. Forecast scenarios until 2040 are presented.

4.1. Goal and Scope

The system boundary remains cradle to gate and is shown in Figure 5. The subsystem of the hydrogen production process is shown in Figure 2. The declared unit is 1 kg of steel. It is assumed that hydrogen is used as the reducing gas for the DR plant as well as for the gas preheater. No scrap input is assumed. The results presented follow the recycled content methodology, so no credits are given for end-of-life scrap [35].

4.2. Life Cycle Inventory

Concerning the DR process, more than 99% of environmentally relevant mass and energy input and output flows are considered. Regarding the electrolysis process with the respective electricity mixes and also for the EAF process, at least 95% of mass and energy input and output flows, and 98% of their environmental relevance are considered according to the GaBi database [11].

The major materials and energy feedstocks of hydrogen-based steel production using a DR plant and an EAF are presented in Table 6. Other inputs, such as nitrogen, coal, and fluxes (Figure 5), are not listed in the table but considered in the carbon footprint assessment according to the defined cut-off criteria. The listed data are the most relevant to the comparison of the assessed scenarios.

Table 6. Major inputs of the processes of electrolysis, hydrogen-based DR plant, and EAF.

Input	(Unit Input/kg Steel)
Iron ore pellets (kg)	1.5
Electricity (MJ)	17 [a]

[a] including electricity for hydrogen electrolysis.

The electricity input for hydrogen electrolysis as well as for the processes of the DR plant and EAF is 17 MJ/kg steel.

Of the 17 MJ electricity input, 2.0 MJ/kg steel is required for the DR plant and the EAF process, whereas 15 MJ/kg steel of electric energy is required as input for the electrolysis process.

4.3. Carbon Footprint Results

Before presenting the results of hydrogen-based steel, the carbon footprint of the intermediate product, DRI, is presented, to separate the effects of hydrogen from those of natural gas (see Figure 8). The carbon footprint of DRI strongly depends on the respective electricity mix that is used for the electrolysis of hydrogen. The respective system boundaries are in line with Figures 2 and 5, but the EAF process is cut off for reasons of comparability. The carbon footprints of the corresponding electricity mixes and hydrogen are presented in Figure 3.

The results show that in three out of four scenarios, it is better, from a climate change perspective, to operate the DR plant with natural gas instead of hydrogen. The carbon footprint of H_2-based DRI in France is comparably low due to a high share of nuclear energy in the national grid mix. The carbon footprint of NG-based DRI is 0.89 kg CO_2eq/kg DRI. In countries with moderate-to-high carbon intensity in electricity production, it is better to use natural gas directly in the DR plant than using hydrogen. In order to reach climate neutrality in the steel industry, national and European grid mixes have to be decarbonized.

Concerning the German and European electricity grid mixes, a forecast scenario until 2040 is presented in Figure 4. Based on this forecast, the expected DRI future carbon footprint is shown in Figure 9. The respective system boundaries are in line with Figures 2 and 5, but the EAF process is excluded to separate the effects of hydrogen from those of natural gas.

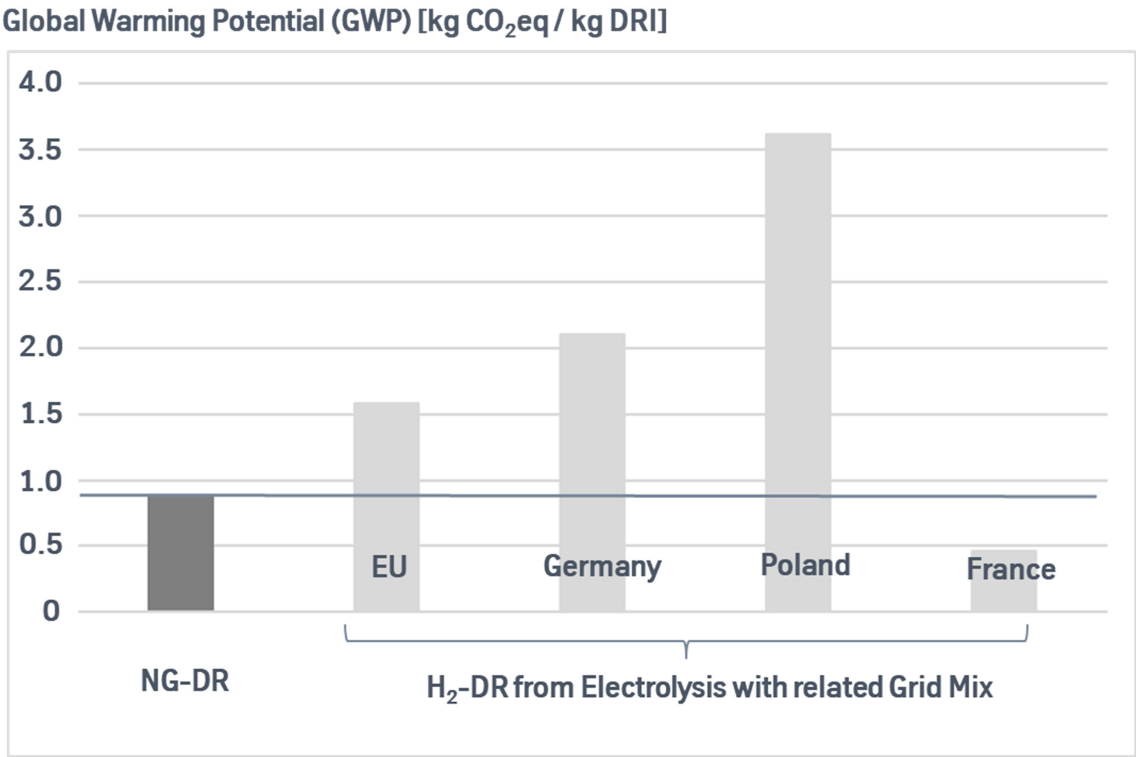

Figure 8. Carbon footprint of direct reduced iron (DRI) depending on the origin of the electricity mix that is used for hydrogen electrolysis for the year 2018. The corresponding electricity mix carbon footprint and the resulting hydrogen carbon footprint are listed in Figure 3.

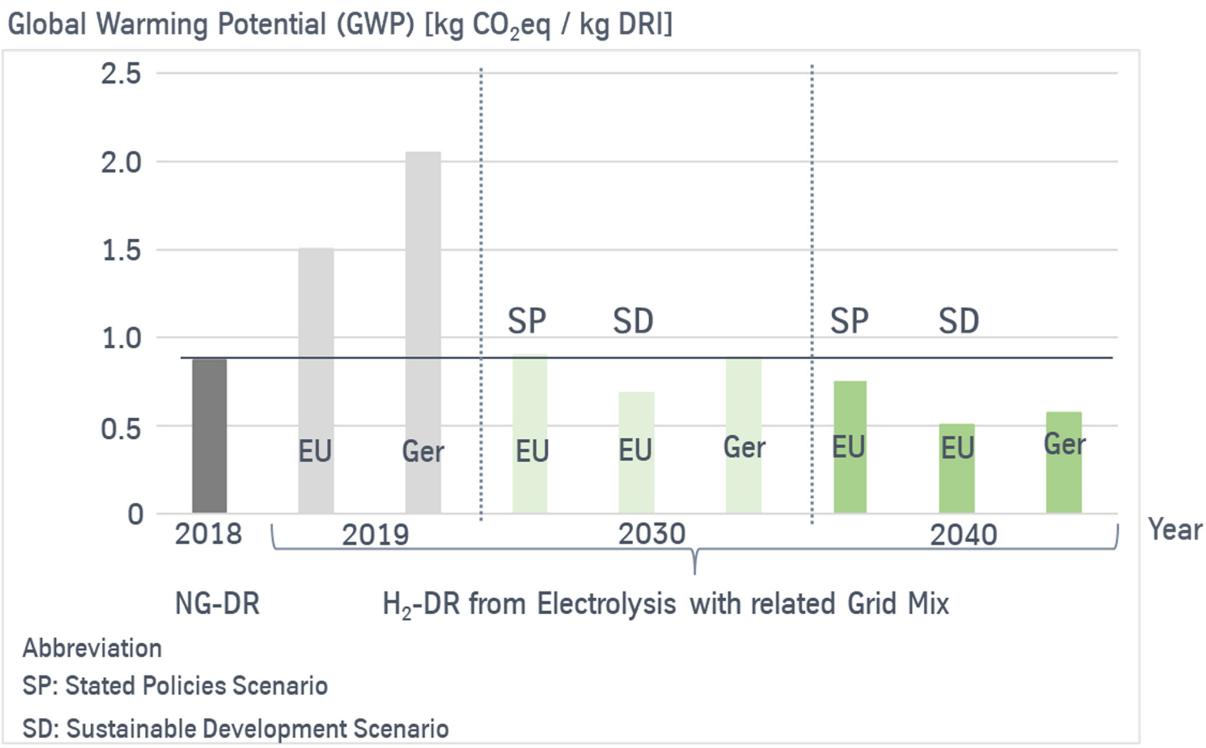

Figure 9. Development of the carbon footprint of direct reduced iron (DRI). For the European development, a stated policy scenario (SP) and a sustainable development scenario (SD) are considered, based on the IEA [34]. The German development scenario is based on Prognos et al. [35]. The carbon footprint of hydrogen in the scenarios are shown in Figure 4.

From 2030 onwards, it would be more preferable to use hydrogen than natural gas for DRI production.

In the following section, hydrogen production with the European grid mix is assumed for the sustainable development scenario for the year 2040. The total impact of steel production on climate change could be reduced by 63% to 0.75 kg CO_2eq/kg steel compared with conventional BF-BOF steel production (see Figure 10).

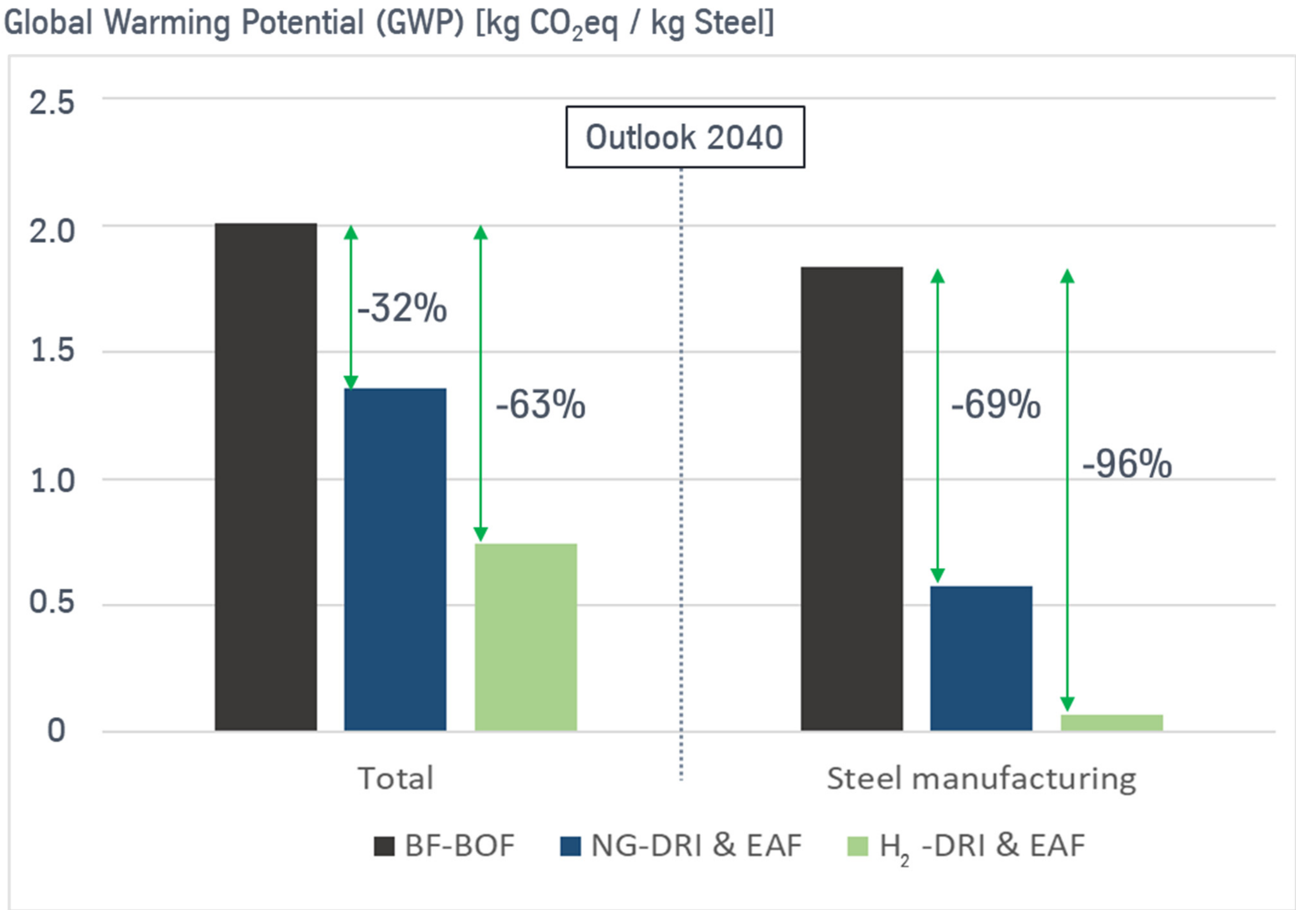

Figure 10. Carbon footprint of steel produced via conventional BF-BOF route, natural gas-based direct reduction–electric arc furnace (NG-DR-EAF) route, and H_2-DR-EAF route. Hydrogen is gained using electrolysis driven by the European grid mix for the year 2040, referring to the sustainable development scenario of the IEA [34] (see Figure 4b).

Whereas the impact of the steel manufacturing processes can be almost zero, there is still a significant amount of impact due to the upstream processes. The categorization is in line with Figure 5. The remaining impact of the manufacturing processes is caused by the addition of coal in the EAF to generate foaming slag. Upstream impacts are mainly caused by the process chain until the product, DRI, is obtained (see Figure 11). In total, 0.56 kg CO_2eq/kg steel is attributed to DRI production. Concerning iron ore pellet production and other raw materials not listed, no incremental improvements are considered.

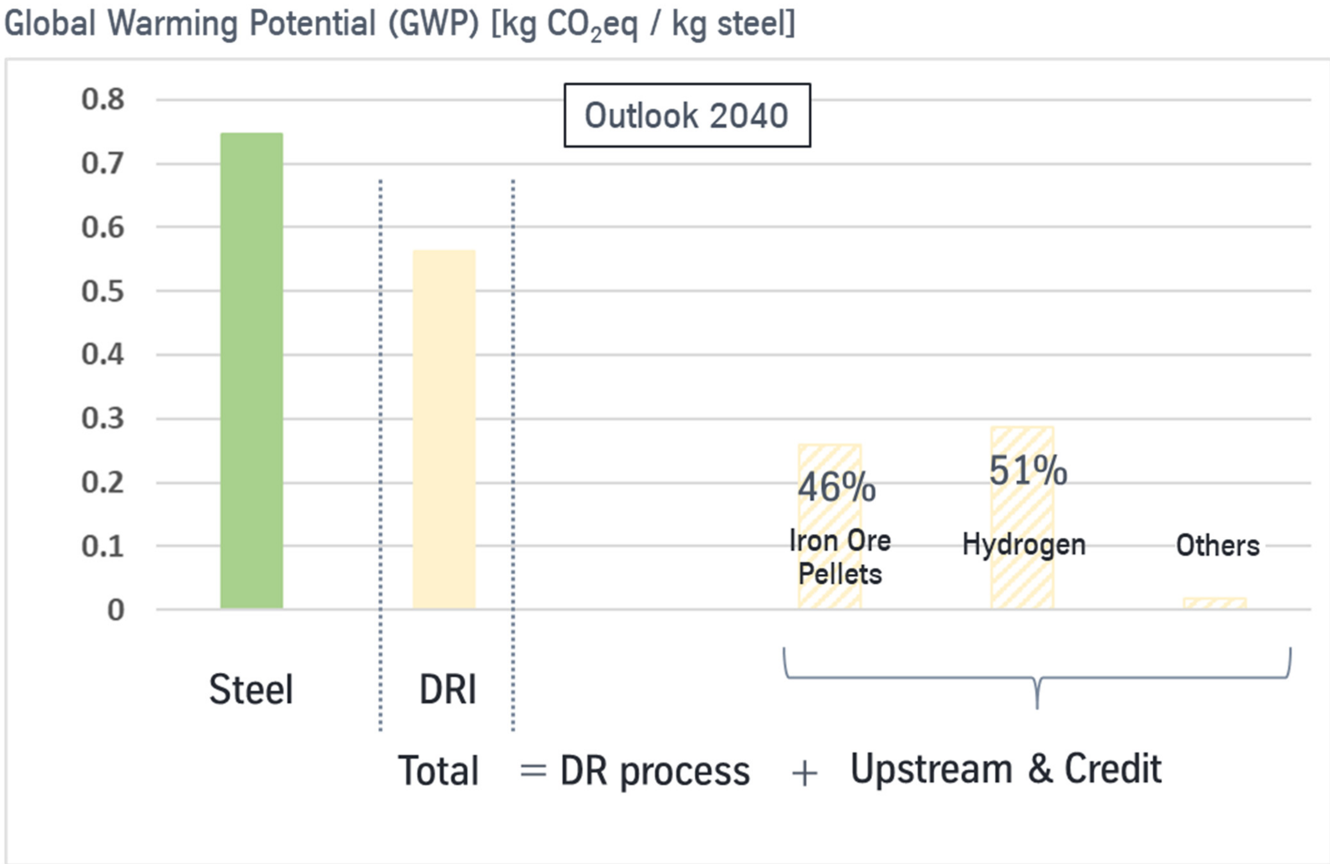

Figure 11. Carbon footprint of steel and impact of the H_2-based DRI production for the year 2040. Hydrogen is produced via electrolysis driven by the European grid mix following the sustainable development scenario in Figure 4 [34].

With 100% hydrogen-based DRI production, the direct impact of the DR process would reach zero. Yet, in order to reach climate-neutral steel production, upstream processes such as iron ore pellet and hydrogen production also have to become climate neutral. In order to further reduce the hydrogen carbon footprint, the electricity mix has to consist out of low-carbon energy. Since steel is an essential construction material for renewable energy sources, e.g., for wind turbines, an improvement of the carbon footprint of steel would ultimately lead to an improvement of the carbon footprint of renewable energy sources and is thus an important building block for other industries.

From the results presented, the carbon footprint of steel can be described in function of the respective electricity mix that is used for the electrolysis of hydrogen, the DR plant, and the EAF (see Figure 12). A constant efficiency of 60.9% (related to the LHV) of the electrolysis process is assumed (Table 2) in order to separate the effects of the electricity mix.

The break-even point of the electricity grid mix carbon footprint is 0.15 kg CO_2eq/kWh. Below this break-even point, the use of hydrogen in a DR plant is superior to the use of natural gas, regarding the impact on climate change. In comparison with the blast furnace route, this break-even point is 0.32 kg CO_2eq/kWh. In the blast furnace route, more electricity is produced in the integrated power plants out of the process gases than it is needed for the steel production route. Thus, excess electricity can be exported to the national grid mix. In Figure 12, no credits for this excess electricity are taken into account. Otherwise, the GWP of steel would be reduced, while the carbon footprint of the national electricity grid mix would be increased. However, the excess electric energy is below 0.2 kWh/kg steel and is of low importance in this comparison.

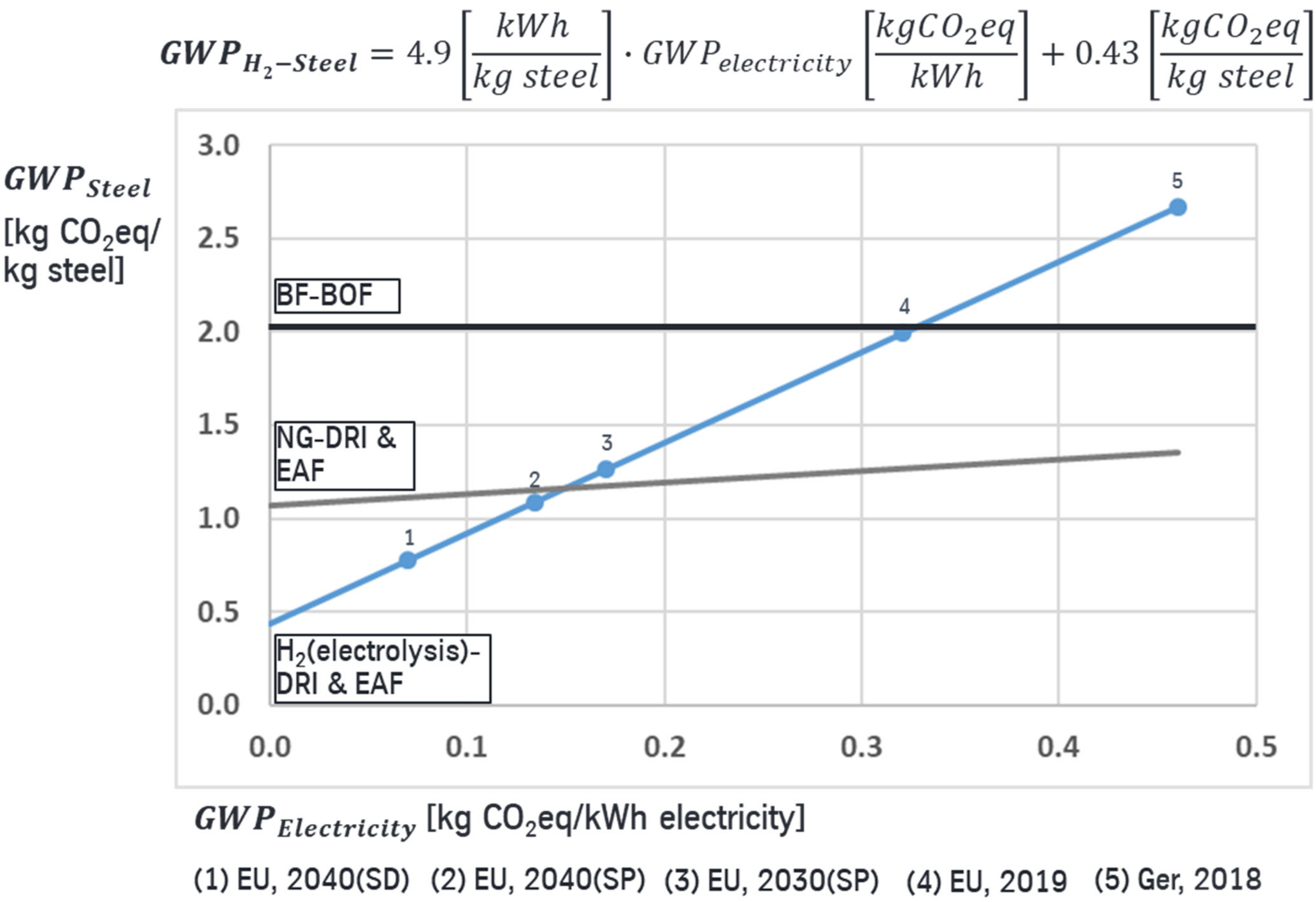

Figure 12. Global warming potential (GWP) of steel, produced using hydrogen-based direct reduction (DR) plant and EAF, in function of the GWP of the electricity mix. Electricity is used for the electrolysis process, the DR plant, and the electric arc furnace (EAF). Abbreviations: SP, stated policy scenario; SD, sustainable development; NG, natural gas.

Steel production using a natural gas-based DR plant is also a function of the electricity grid mix, since electricity is used directly for the DR plant and for the EAF. Yet, the sensitivity is not as high as for the H-DR route, as the electrolysis process for hydrogen production is the most electricity intensive.

5. Conclusions

For the decarbonization of the steel industry, a shift from coal-based towards hydrogen-based metallurgy processes is required. Consequentially, hydrogen production pathways move into focus. Nowadays, hydrogen is mainly produced using fossils fuels; it is not, therefore, a sustainable solution for a real transformation. Hydrogen production using water electrolysis, driven by electricity, gains more importance; thus, electricity production moves into focus.

The impact of the related electricity mix on the produced hydrogen carbon footprint is investigated and is compared to the state of the art of hydrogen production in this paper. Accordingly, a literature analysis is presented, including different current scenarios of hydrogen production. For the hydrogen production using electrolysis, several national grid mixes as well as the European grid mix are considered, focusing on forecasts for the years 2030 and 2040. These results are integrated into a carbon footprint assessment of steel produced via direct reduction plants (DR plants) combined with electric arc furnaces (EAFs). However, the results concerning the hydrogen production gained in this paper can also be transferred to other industries.

The carbon footprint of steel produced using natural gas-based direct reduction combined with an integrated EAF (NG-DRI-EAF route) is 1.4 kg CO_2eq/kg steel. Compared with the carbon footprint of current state-of-the-art primary steel produced using the conventional BF-BOF route of 2.0 kg CO_2eq/kg steel, a significant reduction potential of 32% can be achieved. The carbon footprint of steel produced via the H_2-DRI-EAF route largely depends on the carbon footprint of the consumed hydrogen.

The break-even point of the electricity grid mix carbon footprint is 0.15 kg CO_2eq/kWh. Below this break-even point, the use of hydrogen from electrolysis in a DR plant is superior to the use of natural gas regarding the impact on climate change. For the German and European grid mixes, this break-even point is predicted to be reached from 2030 onwards. Before 2030, the use of natural gas is superior to hydrogen from a carbon footprint assessment perspective. The break-even point, compared with the blast furnace route, is 0.32 kg CO_2eq/kWh. Below this value, hydrogen-based steel production is superior to the conventional coal-based blast furnace route.

By the year 2040, the steel produced via the H_2-DR-EAF route is anticipated to have a carbon footprint of about 0.75 kg CO_2eq/kg steel, following the sustainable European grid mix forecast. Therefore, the impact of the manufacturing processes of the steel industry on climate change can almost reach the value of zero. However, to achieve complete climate neutrality, the upstream impact of supply chains also needs to be decarbonized. In this context, the carbon footprint of renewable electricity is a significant measurement. Since steel is an essential construction material for renewable energy sources, e.g., for wind turbines, an improvement of the carbon footprint of steel would ultimately lead to an improvement of the carbon footprint of renewable energy sources.

Steel can play a meaningful role in the sustainable transformation of industry and society to achieve European climate targets.

The limitations of the study are that only impacts on climate change are considered. Especially with respect to nuclear-based electricity production, the consideration of other environmental impact categories could also prove to be significant. Yet, for hydrogen- and electricity-based steel production, the data are based on metallurgical models due to the lack of primary data from practical field tests. In a life cycle sustainability assessment (LCSA), the economic and social pillars of these scenarios could also be investigated.

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References

1. IPCC. Climate Change 2021: The Physical Science Basis. In *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Eds.; Cambridge University Press: Cambridge, UK, 2021.
2. European Union (EU). Communicatio n from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. 2019. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF (accessed on 21 January 2022).
3. Federal Constitutional Court. Constitutional Complaints against the Federal Climate Change Act Partially Successful. 2021. Available online: https://www.bundesverfassungsgericht.de/SharedDocs/Pressemitteilungen/EN/2021/bvg21-031.html. (accessed on 21 January 2022).
4. IEA. International Energy Agency: Iron and Steel Technology Roadmap—Towards More Sustainable Steelmaking. 2020; pp. 38–43. Available online: https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf (accessed on 21 January 2022).

5. Worldsteel Association. Setting the Course for a Healthy Steel Industry. 2020. Available online: https://www.steelforum.org/stakeholders/gfsec-march-2020-worldsteel.pdf (accessed on 11 November 2021).
6. Wang, P.; Ryberg, M.; Yang, Y.; Feng, K.; Kara, S.; Hauschild, M.; Chen, W.-Q. Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. *Nat. Commun.* **2021**, *12*, 2066. [CrossRef]
7. Wörtler, M.; Schuler, F.; Voigt, N.; Schmidt, T.; Dahlmann, P.; Lüngen, H.B.; Ghenda, J. Steel's Contribution to a Low-Carbon Europe 2050. Technical and Economic Analysis of the Sector's CO_2 Abatement Potential. 2013. Available online: https://www.stahl-online.de/wp-content/uploads/Schlussbericht-Studie-Low-carbon-Europe-2050_-Mai-20131.pdf (accessed on 10 December 2022).
8. *DIN EN ISO 14040:2006 + Amd 1:2020*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
9. *DIN EN ISO 14044:2006 + Amd 1:2017 + Amd 2:2020*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
10. *DIN EN ISO 14067:2019-02*; Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification. ISO: Geneva, Switzerland, 2019.
11. ©Sphera Solutions GmbH. Gabi Database 2021.1. List of Databases. 2021. Available online: https://gabi.sphera.com/databases/gabi-data-search/ (accessed on 10 December 2022).
12. Suer, J.; Traverso, M.; Ahrenhold, F. Carbon footprint of scenarios towards climate-neutral steel according to ISO 14067. *J. Clean. Prod.* **2021**, *318*, 128588. [CrossRef]
13. Liu, W.; Zuo, H.; Wang, J.; Xue, Q.; Ren, B.; Yang, F. The production and application of hydrogen in steel industry. *Int. J. Hydrogen Energy* **2021**, *46*, 10548–10569. [CrossRef]
14. Agora Energiewende. Klimaneutrale Industrie. Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement. Berlin. November 2019. Available online: https://www.agora-energiewende.de/veroeffentlichungen/klimaneutrale-industriehauptstudie/ (accessed on 8 March 2022).
15. Midrex Technologies, Inc. Direct from Midrex, 2nd Quarter. 2019. Available online: http://www.midrex.com/wp-content/uploads/Midrex_2019_DFM2QTR_Final.pdf (accessed on 23 November 2022).
16. Suer, J.; Traverso, M.; Jäger, N. Review of Life Cycle Assessments for Steel and Environmental Analysis of Future Steel Production Scenarios. *Sustainability* **2022**, *14*, 14131. [CrossRef]
17. Duarte, P.E.; Becerra, J.; Lizcano, C.; Martinis, A. ENERGIRON direct reduction technology-economical, flexible, environmentally friendly. *Acero Lat.* **2008**, *6*, 52–58.
18. Federal Ministry of Education and Research. Eine kleine Wasserstoff-Farbenlehre. 2021. Available online: https://www.bmbf.de/de/eine-kleine-wasserstoff-farbenlehre-10879.html (accessed on 21 January 2022).
19. IEA. International Energy Agency: Hydrogen—Fuels & Technologies—IEA. 2021. Available online: https://www.iea.org/fuels-and-technologies/hydrogen (accessed on 21 January 2022).
20. Dena. Deutsche Energie-Agentur GmbH (dena)—German Energy Agency. Sustainable Electricity Sources. Renewable Fuels of Non-Biological Origin in the RED II. 2020. Available online: https://www.dena.de/test/user_upload/Sustainable_Electricity_Sources_Position_Paper_2020-07.pdf (accessed on 21 January 2022).
21. Hölling, M.; Schäfers, H.; Gellert, S.; Grasenack, M.; Jürgens, L.; Tedjosantoso, N.; Schüttler, S. *WiSaNo—Windstahl aus Norddeutschland*. Technical Report. 2021. Available online: https://germany.arcelormittal.com/icc/arcelor/med/f53/f53689fc-e1fa-9718-60c5-e74064a585a0,11111111-1111-1111-1111-111111111111.pdf (accessed on 10 December 2022). [CrossRef]
22. Ozbilen, A.; Dincer, I.; Rosen, M.A. A comparative life cycle analysis of hydrogen production via thermochemical water splitting using a Cu–Cl cycle. *Int. J. Hydrogen Energy* **2011**, *36*, 11321–11327. [CrossRef]
23. Cetinkaya, E.; Dincer, I.; Naterer, G. Life cycle assessment of various hydrogen production methods. *Int. J. Hydrogen Energy* **2011**, *37*, 2071–2080. [CrossRef]
24. Antonini, C.; Treyer, K.; Streb, A.; van der Spek, M.; Bauer, C.; Mazzotti, M. Hydrogen production from natural gas and biomethane with carbon capture and storage—A techno-environmental analysis. *Sustain. Energy Fuels* **2020**, *4*, 2967–2986. [CrossRef]
25. Mehmeti, A.; Angelis-Dimakis, A.; Arampatzis, G.; McPhail, S.J.; Ulgiati, S. Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies. *Environments* **2018**, *5*, 24. [CrossRef]
26. Bukold, S.; Huneke, F.; Claußner, M. Studie Grün oder Blau? Wege in die Wasserstoff-Wirtschaft 2020 bis 2040. 2020. Available online: https://green-planet-energy.de/fileadmin/docs/pressematerial/Gruen_oder_blau_Wege_in_die_Wasserstoffwirtschaft_final.pdf (accessed on 10 December 2022).
27. Vickers, J. Current Central Hydrogen from Coal with CO_2 Capture and Sequestration version 3.2018. 2019. Available online: https://www.nrel.gov/hydrogen/h2a-production-models.html (accessed on 21 January 2022).
28. Bartlett, J.; Krupnick, A. Resources for the Future Report: Decarbonized Hydrogen in the US Power and Industrial Sectors: Identifying and Incentivizing Opportunities to Lower Emissions. 2020. Available online: https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors/ (accessed on 21 January 2022).
29. van Cappellen, L.; Croezen, H.; Rooijers, F. Feasibility Study into Blue Hydrogen. Technical, Economic & Sustainability Analysis. CE Delft. 2018. Available online: https://cedelft.eu/wp-content/uploads/sites/2/2021/04/CE_Delft_9901_Feasibility_study_into_blue_hydrogen_DEF_bak.pdf (accessed on 21 January 2022).

30. Howarth, R.W.; Jacobson, M.Z. How green is blue hydrogen? *Energy Sci. Eng.* **2021**, *9*, 1676–1687. [CrossRef]
31. Dawood, F.; Anda, M.; Shafiullah, G.M. Hydrogen Production for Energy: An Overview. *Int. J. Hydrog. Energy* **2020**, *45*, 3847–3869. [CrossRef]
32. Office of Energy Efficiency & Renewable Energy. Safe Use of Hydrogen. 2022. Available online: https://www.energy.gov/eere/fuelcells/safe-use-hydrogen (accessed on 21 November 2022).
33. IEA. International Energy Agency: Electricity Generation by Source. 2018. Available online: https://www.iea.org/countries (accessed on 21 January 2022).
34. IEA. *International Energy Agency: World Energy Outlook (2020)*; OECD Publishing: Paris, France, 2020. [CrossRef]
35. Prognos, Öko-Institut, Wuppertal-Institut. Klimaneutrales Deutschland. Studie im Auftrag von Agora Energiewende, Agora Verkehrswende und Stiftung Klimaneutralität. 2020. Available online: https://www.agora-energiewende.de/veroeffentlichungen/klimaneutrales-deutschland/ (accessed on 21 January 2022).
36. Prognos, A.G. Kosten und Transformationspfade für strombasierte Energieträger. With assistance of Kreidelmeyer, S.; Dambeck, H.; Kirchner, A.; Wünsch, M. 2020. Available online: https://www.bmwi.de/Redaktion/DE/Downloads/Studien/transformationspfade-fuer-strombasierte-energietraeger.pdf?__blob=publicationFile (accessed on 21 January 2022).
37. World Steel Association. *Life Cycle Assessment Methodology Report*; World Steel Association: Brussels, Belgium, 2011.
38. Sarkar, S.; Bhattacharya, R.; Roy, G.G.; Sen, P.K. Modeling MIDREX Based Process Configurations for Energy and Emission Analysis. *Steel Res. Int.* **2017**, *89*. [CrossRef]
39. Barati, M. Energy intensity and greenhouse gases footprint of metallurgical processes: A continuous steelmaking case study. *Energy* **2010**, *35*, 3731–3737. [CrossRef]
40. Cardenas, J.G.G.; Conejo, A.N.; Gnechi, G.G. Optimization of energy consumption in electric arc furnaces operated with 100% DRI. *Metal* **2007**, *2017*, 1–7.

3 Discussion

This chapter provides the key findings of life cycle assessments of steel. Opportunities and challenges for a decarbonized steel production are outlined. Limitations of this dissertation are described.

3.1 Key findings

This dissertation evaluates decarbonization pathways of the steel industry from a technical and environmental perspective. Using the LCA and PCF methodology, holistic approaches are followed. The state-of-the art is presented for contemporary LCA studies with focus on the primary BF-BOF route and the secondary scrap-based EAF route. A carbon footprint assessment is conducted for an integrated steel site at the example of thyssenkrupp Steel Europe in Duisburg using data from 2018. The PCF of the product is 2.1 kg CO_2eq/kg HRC. The direct impact of the processes of the integrated site, including a sinter plant, coke plant, BF, BOF, casting, and hot-rolling is 1.9 kg CO_2eq/kg HRC. The upstream impact through imported material and energy flows is 0.6 kg CO_2eq/kg HRC. Main upstream impacts are production and transportation of: coal (0.2 kg CO_2eq/kg HRC), iron ore pellets (0.08 kg CO_2eq/kg HRC) iron ores (0.05 kg CO_2eq/kg HRC), alloying elements (0.1 kg CO_2eq/kg HRC, quicklime (0.08 kg CO_2eq/kg HRC), and oxygen (0.02 kg CO_2eq/kg HRC). Credits for co-products add up to 0.4 kg CO_2eq/kg HRC. Co-products substitute primary production in other industries. Main co-products are: BF slag, BOF slag, surplus electricity, tar, benzene, and sulfur.

It is pointed out that breakthrough technologies especially within the primary steel production route are needed. A shift from primary to secondary steel production could only reduce regional environmental impacts but not on a global scale. The evaluation of the recycling potential of steel in LCAs is pointed out in detail within the review paper of this dissertation.

The DR process is found to be a key technology for the decarbonization pathway. Presently, DR plants, in combination with electrical melting, can compete with the capacities of modern blast furnaces. Both, a natural gas, as well as a hydrogen-based DR process are analyzed. Regarding the melting step, (1) the use of DRI in a melting unit and subsequent BOF, and (2) the use of DRI in an EAF are considered and assessed using PCF methodology. The carbon footprint of a hydrogen and electricity-based steel can be reduced to about 0.75 kg CO_2eq/kg HRC. Thereby no incremental improvements are assumed concerning the upstream processes such as the production of pellets, alloying elements, quicklime or the generation of renewable electricity and hydrogen. However, the electricity mix is assumed to be completely from renewable sources for hydrogen electrolysis and for the steel production aggregates. If the electricity input is not renewable but e.g., from the German grid mix of 2018, the PCF increases up to 3.0 kg CO_2eq/kg HRC and is thus ultimately higher than the PCF from a BF. In this case it would be beneficial to use natural gas within the DR plant from a climate change perspective. The PCF of a natural gas-based steel production is 1.4 kg CO_2eq/kg HRC, if the electricity input is renewable and up to 1.7 kg CO_2eq/kg HRC, if the German grid mix for 2018 is considered for electricity supply. A detailed break-even analysis is part of this dissertation.

Carbon footprint assessments are presented for several electricity and hydrogen production scenarios and their impact on the resulting steel's carbon footprint. Whereas a traditional coal-based steel site produces a surplus of electricity due to large amounts of process gases, this surplus turns into a deficit, when direct reduction plants and electric melting aggregates replace blast furnaces. An electricity demand of 4.7 to 4.9 kWh/kg steel is identified in this dissertation considering the two pathways (1) the use of H_2-DRI in an electric melting unit and BOF and (2) use of H_2-DRI in an EAF. These values include electricity demand for hydrogen electrolysis.

In the H_2-DR route, the direct carbon footprint of the processes of the integrated site, including a DR plant, electric melting unit, BOF, casting, and subsequent hot-rolling can be reduced to about 0.15 kg CO_2eq/kg HRC. The remaining impact maintains that the steel industry may rely on a biogenic carbon source in the future. The CO_2eq emissions result from carbon monoxide-rich off-gases. These are valuable gases for the chemical industry. Both industries could benefit from a long-term cross-functional cooperation. Likewise, the cooperation between the steel and cement industry should be continued, which saves resources and reduces impacts on the climate change. Therefore, further research is essential, which is further discussed in section 3.2.

Intermediate scenarios can enable and push transformation pathways. Four modifications of the BF process are highlighted in this dissertation. It is shown that the PCF can be reduced by up to 9% for injecting hydrogen into a BF. Using H_2-based HBI in a BF can reduce the PCF between 10% and 17%. The reduction potential strongly depends on the iron feedstock, which is replaced by the HBI. Intermediate scenarios are able to couple technical integration of new processes or materials in an integrated site with simultaneously first reductions of environmental impacts.

3.2 Challenges

A huge challenge for the transformation of the steel industry is the supply of renewable energy, which will be required for a decarbonized steel production. As mentioned, integrated steel plants will transform from electricity producers to consumers, and it was found that about 4.7 to 4.8 kWh/kg HRC are required if primary energy is shifted from coal towards electricity. To illustrate this tremendous challenge, the consequence for German steel producers and for the German energy mix is described:

In Germany, about 28 million tonnes of steel are produced via the BF route in 2021 [5]. If these were produced via the H_2-DR route in the future, this would lead to a renewable electricity demand of around 130 TWh per year. In comparison, Germany has produced about 600 TWh of electricity in 2021 in total (fossil, nuclear, renewable) [27]. This is a tremendous challenge for both, steel producers and society.

Steel producers will face the challenge to produce high quality steels from partially new production routes. Although a large-scale hydrogen-rich (H_2 content of 55-86 volume-%) shaft furnace direct reduction process has been proven [28], a 100% hydrogen-based production will be the first of its kind.

The further treatment of the DRI is intensively discussed within the steel industry. Two main routes stand out, which both have advantages and challenges, which shall be explained in the following:

1. Processing of DRI in an EAF to crude steel
2. Processing of DRI in an electric melting unit (e.g., an open slag bath furnace) to hot metal, and refining the hot metal in classical BOFs to crude steel

In route (1) DRI is melted and produced to crude steel in an EAF. The EAF process step is comparable to scrap recycling in an EAF, today but there are differences, which require attention. DRI still contains the gangue from the ore and the metallization is typically assumed to be about 95% leading to a FeO content of roughly 5% [29]. In an EAF oxygen and carbon are injected during the refining period to form CO, which homogenizes the bath, flushes out dissolved gases like hydrogen and nitrogen, and foams the slag to encompass the electrodes. During the refining period, elements like phosphorous, silicon, and manganese are oxidized and transferred into the slag (see chapter 1). An undesirable effect is that iron is also oxidized and transferred as FeO into the slag, which decreases the iron yield. Depending on the operation mode, the FeO content of the slag can be between 20 to 40% in a scrap-based EAF process [30,31]. Furthermore, the use of DRI, which still contains gangue and FeO, can lead to unacceptably high amounts of slag in an EAF for process control [31,32]. This in turn can be reduced by using high-grade iron ore pellets in the DR process, which have limited amounts of gangue and preferably low silica or alumina quantities, which require more than equal addition of basic fluxes to keep the slag within acceptable parameters in the EAF [30,31]. However, the supply of high-grade pellets is limited and shortages are predicted with increasing amounts of DR plants [31,32]. Another option is the mixture of DRI with scrap in an EAF, which presents both an opportunity as well as a challenge. Unlike DRI, scrap does not contain gangue, which reduces the amount of slag. On the other hand, scrap contains impurities, which limits the quality of the final product, as mentioned in section 1. However, scrap recycling is a resource-, emission- and energy efficient way of producing steel, which should be continued. Moreover, demand for lower quality steels also exists. Thus, this route can be perfectly complemented by the second route, which is presented in the following section.

In route (2) DRI is processed to hot metal in an electric melting unit. In contrast to the EAF process no refining step is foreseen in this unit so no oxygen is injected. Instead, carbon is inserted for two main reasons:

1. to reduce the remaining FeO in the DRI;
2. to carburize the hot metal.

Reason (1) improves the iron yield of the process and lessens the amount of produced slag. Since no additional oxygen is injected, which stimulates the production of slag for quality improvement, the amount of produced slag is limited in this process step. Nevertheless, the refining step is necessary, but it is relocated to the next process unit – the conventional BOF. Thus, slag production is divided over two processes, the electric melting unit, in which the gangue of the DRI is removed, and the BOF, in which elements like phosphorous, silicon, manganese are oxidized and transferred into the slag. This division of one process step into two enables an optimized slag control, which facilitates the use of low-quality iron ore pellets. Another advantage is the fact that the product of the melting unit, hot metal, substitutes the hot metal from BFs, eliminating the need to change the downstream processes. The BOF process has proven to produce high quality steels if the lowest grades of nitrogen, phosphorous, or carbon are required [publication III]. In addition, very practical reasons such as harmonised tapping weights and times between process steps are simplified, as an existent process structure can be maintained.

Like in an EAF, the forming of CO bubbles in a BOF improves the steel quality and the process control. Dissolved gases like hydrogen and nitrogen are flushed out, the bath is homogenized, and the CO bubbles generate a good metal - slag contact. Due to this, it is comprehensible that the product of the electric melting unit should still contain carbon, like the hot metal from a BF does today. An interesting research question is the amount of carbon, which the product from the melting unit should have. The carbon content of the hot metal from a BF is about 4.5% for process related reasons. The hot metal from an electric melting unit does not necessarily need to have the same carbon content. A lower carbon content could also be sufficient for the BOF process, which ultimately reduces the carbon input and thus CO_2 emissions.

Another benefit of route (2) is that the slag generated by the electric melting unit could principally have the same characteristics as conventional BF slag, and thus serves as clinker cement substitute. Since carbon is inserted and no oxygen is injected the FeO is reduced and not transferred into the slag. This is an important characteristic for slag, which is used for the cement industry. Further research is required for an optimized slag production in both production routes. Additionally, complete LCA studies considering more impact categories are required for the slags, which will be produced via the two routes.

To sum up, with the second route the continuation of producing high quality steels from natural iron ores seems very realistic. The first route benefits from combining scrap recycling with primary production but depends on higher grades of iron ores or scrap, which limits the product quality. Whereas route (1) enables a good scrap recycling potential, route (2) ensures the production of high-quality steel from iron ores. Both are required for future steel production and these two routes could complement one another.

A challenge of both routes is that they still depend on a source for carbon. For the second route a minimum carbon demand leads to 150 kg CO_2eq/t HRC, which is identified in this publication. Thus, future steel production could rely on a biogenic resource. Other (additional) options could be carbon loops, CCU, or CCS.

A further challenge is the economic barrier. For the H_2-DRI-EAF route the costs for steel production under optimal conditions are increased by 350€/t steel, which is equivalent to a carbon dioxide abatement cost of 200 €/t CO_2 regarding to an integrated BF-BOF site [33]. These costs are far above the steel producer's usual margin of profit and companies by themselves cannot overcome these challenges [33,34]. Lechtenböhmer and Fischedick (2020) [34] give a survey of policy and market-based strategies on how the decarbonization pathway can be enabled despite the economic barrier. They determine five key aspects of an integrated climate and industrial policy, which is briefly summarized in the following:

1. It must support the development of a renewable energy supply infrastructure in quantities that can satisfy the needs of the industries.
2. It must provide long-term economic incentives for climate neutral investments. A minimum CO_2 price in combination with border tax adjustments could be part of the solution.
3. Innovative projects for GHG emission reductions can be funded.
4. Market-based measures such as the establishment of "green product markets" can provide permanent incentives. A demand for "green products" must be ensured, e.g., by quotas or standards in public projects.
5. Development of innovative concepts and instruments to promote the use of fewer materials in combination with high recycling rates. [34]

To sum up, decarbonizing the steel industry strongly depends on the success of the energy transition towards renewables. This is a global social challenge, which needs to be dealt with. The steel industry itself will also face metallurgical challenges. Yet, the required processes are not entirely new and can be built on established knowledge. In combination with further research and development the steel industry has a promising future.

3.3 Limitations

For the future steel production scenarios PCF assessments are conducted in this dissertation. The data quality was not sufficient for complete LCAs since the data are based on metallurgical models, which focus on GHG emissions. The technologies are evaluated in terms of resulting carbon footprints for the product steel and the related energy transformation. Changes in other life cycle impact categories such as eutrophication potential or acidification potential etc. are not assessed for future steel production scenarios.

In sum, the steel transformation will lead to a shift from coal towards electricity demand. Trade-offs between different impact categories are possible. E.g., renewable electricity and hydrogen production require elementary abiotic resources such as platinum, silver, lithium, or copper etc. Increased nuclear energy can increase the impact category ionizing radiation. Coal on the other hand contains carbon, sulfur, and phosphorous, which increases the GWP, AP, EP, or the photochemical ozone creation potential (POCP). These trade-offs should be evaluated in LCAs when sufficient data quality is given.

Another limitation is the fact that the data for the future steel production scenarios are based on metallurgical models and not on primary data.

Many stakeholders such as workers, value chain actors, society, and local communities are affected by the steel transformation. These social aspects should be assessed in a social LCA.

4 Conclusion and outlook

This section summarizes the added value of this dissertation and gives recommendations for future research.

A product carbon footprint for steel, produced via a classical integrated steel site, is presented. The calculation of the assessment is based on primary data provided for the integrated site of thyssenkrupp Steel Europe AG, for year 2018. This PCF describes the state-of-the art. Within a novel approach this baseline is enhanced by incorporating metallurgical models. Four intermediate scenarios are considered, (1) the injection of NG into a BF, (2) the injection of hydrogen into a BF, (3) the use of NG-based HBI in a BF, and (4) the use of H_2-based HBI in a BF. In doing so, all changes of the complex material and energy supply chain are considered, and a PCF is presented for these scenarios.

PCF assessments are presented for the DR-based steel production scenarios. Both, NG and H_2-based DR processes are analyzed. The use of DRI in an electric melting unit with further refining of the hot metal in a BOF as well as the use of DRI in an EAF are considered. In addition, special focus is given to hydrogen and electricity production, and PCFs are assessed for different production routes until the year 2040. The findings can help policy makers and steel producers estimate how much renewable electric energy will be required for the decarbonization of the steel industry.

For the listed scenarios, metallurgical challenges are intensively discussed, and solutions are presented. Special attention is paid to the intermediate scenarios and a comparison between the DR-based production routes. An interesting research question was identified on how much carbon the product from an electric melting unit should have for further refining in a BOF.

Limitations of this dissertation are that the data for the future scenarios are based on metallurgical models. Since these models generally focus on CO_2 emissions, the sole impact category climate change is assessed for these production routes in this dissertation. In future research, the PCF assessments should be enhanced by LCAs by considering other relevant impact categories and primary data can used instead of metallurgical models.

The transformation of the steel industry, in particular the required energy transition, is a huge challenge for both the steel industry and society. These transformations will affect several stake holders such as workers, value chain actors, society, and local communities. The social life cycle assessment methodology allows for the estimation and quantification of such potential social impacts, which can facilitate a social fair transformation.

References

[1] IPCC. Climate Change 2021: The Physical Science Basis. In Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Eds.; Cambridge University Press: Cambridge, UK, 2021.

[2] European Union (EU). Communicatio n from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. 2019. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF (accessed on 21 January 2022).

[3] IEA. International Energy Agency: Iron and Steel Technology Roadmap—Towards More Sustainable Steelmaking. 2020. pp. 38–43. Available online: https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf (accessed on 21 January 2022).

[4] Tönjes, A.; Lechtenböhmer, S.; Leipprand, A.; Zelt, O. Klimaneutraler Stahl Made in Germany: Transformationsherausforderungen im Kontext steigender Marktanforderungen. 2022. Available online: https://epub.wupperinst.org/frontdoor/deliver/index/docId/7924/file/7924_Toenjes.pdf (accessed on 10 October 2022).

[5] Worldsteel Association. Worldsteel in figures 2022. Available online : https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2022-1.pdf (accessed on 19 Dec. 22)

[6] Wang, P.; Ryberg, M.; Yang, Y.; Feng, K.; Kara, S.; Hauschild, M.; Chen, W.-Q. Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. Nat. Commun. 2021, 12, 2066.

[7] Bouckaert, S.; Pales, A. F.; McGlade, C.; Remme, U.; Wanner, B., Varro, L.; Ambrosio, D.; Spencer, T. (2021). Net Zero by 2050: A Roadmap for the Global Energy Sector.

[8] Berger, R. The Future of Steelmaking. How the European Steel Industry Can Achieve Carbon Neutrality; Roland Berger GMBH: Munich, Germany, 2020.

[9] Fischedick, M., Marzinkowski, J., Winzer, P., Weigel, M., 2014. Techno-economic evaluation of innovative steel production technologies. J. Clean. Prod. 84, 563–580. https://doi.org/10.1016/j.jclepro.2014.05.063.

[10] Agora Energiewende. Klimaneutrale Industrie. Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement. Berlin, November 2019. Available online: https://www.agora-energiewende.de/veroeffentlichungen/klimaneutrale-industriehauptstudie/ (accessed on 8 March 2022).

[11] Zhang, T.; Fletcher, A.; Rossouw, I. Barclays. What if… Smelter Furnaces are the future of steelmaking? European Metals & Mining. United Kingdom, 2022.

[12] ISO 14040; DIN EN ISO 14040:2006 + Amd 1:2020. Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.

[13] ISO 14044; DIN EN ISO 14044:2006 + Amd 1:2017 + Amd 2:2020. Environmental Management—Life Cycle Assessment— Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.

[14] DIN EN ISO 14067:2019-02; Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification. ISO: Geneva, Switzerland, 2019.

[15] Gudenau, H.W.; Gebel, U.; Gerlach,W.; Grandin, F.H.; Guntermann, K.; Hoberg, H.; Kim, S.; Koerfer, M.; Mulanza, J.P.; Pintsch, S.; et al. Eisenhüttenmännische Verfahrenstechnik. Vom Erz zum Stahl; Druck-& Verlagshaus MAINZ GmbH: Aachen, Germany, 1989.

[16] Bartos, R.; Brockmann, S.; Fandrich, R.; Endemann, G.; Ghenda, J.T.; Heinzel, S.; Letz, K.; Lüngen, H.B.; Moninger, G.; Stellmacher, U.; et al. VDEh Stahlfibel; Verlag Stahleisen GmbH, Düsseldorf, 2015.

[17] Dutta, S.K.; Chokshi, Y.B. Basic Concepts of Iron and Steel Making; Springer: Berlin/Heidelberg, Germany, 2020.

[18] MacRosty, R.D.M.; Swartz, C.L.E. Dynamic optimization of electric arc furnace operation. AIChE J. 2007, 53, 640–653. https://doi.org/10.1002/aic.11104.

[19] Rekersdrees, T.; Schliephake, H.; Schulbert, K. (2014). Aufbau und Prozessführung des Lichtbogenofens unter besonderer Berücksichtigung des Schlackenmanagements. Available online: https://www.vivis.de/wp-content/uploads/SaM3/2014_SaM_209-230_Schliephake.pdf (accessed on 04 January 2023).

[20] Arribas, I., Santamaría, A., Ruiz, E., Ortega-López, V., & Manso, J. M. (2015). Electric arc furnace slag and its use in hydraulic concrete. Construction and Building Materials, 90, 68-79. https://doi.org/10.1016/j.conbuildmat.2015.05.003

[21] Liu, W.; Zuo, H.; Wang, J.; Xue, Q.; Ren, B.; Yang, F. The production and application of hydrogen in steel industry. Int. J. Hydrogen Energy 2021, 46, 10548–10569.

[22] Midrex Technologies, Inc. Direct from Midrex, 2nd Quarter. 2019. Available online: http://www.midrex.com/wp-content/uploads/Midrex_2019_DFM2QTR_Final.pdf (accessed on 23 November 2022).

[23] Duarte, P.; Becerra, J.; Scarnati, T. ENERGIRON direct reduction technology—Economical, flexible, environmentally friendly. Acero LatinoAmericano 2008, 6, 52–58.

[24] IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926

[25] DIN EN 15804:2012+A2:2019. Sustainability of construction Works – Environmental product declarations – Core rules for the product category of construction products;

[26] European Commission - Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union; 2010

[27] International Energy Agency (IEA): Key energy statistics. Available online: https://www.iea.org/countries/germany (accessed on 24 January 2023).

[28] Wang RR, Zhao YQ, Babich A, Senk D, Fan XY (2021) Hydrogen direct reduction (H-DR) in steel industry—An overview of challenges and opportunities. J Clean Prod 329:129797. https:// doi.org/ 10. 1016/j. jclep ro. 2021. 129797

[29] Hölling, M., Gellert, S. (2018). Vom Erdgas zum Wasserstoff – Zeit für einen Wechsel bei der Direktreduktion? Aachener Stahl-Kolloquium Conference (32). Available online: https://www.researchgate.net/publication/351579220_Vom_Erdgas_zum_Wasserstoff_Zeit_fur_einen_Wechsel_bei_der_Direktreduktion (accessed on 24 January 2023).

[30] Stagnoli, P. (2020). Decarbonising the steelmaking process. Steel Times International, 44(5), 24-27. Available online:

[31] Lüngen, I. H. B., & Schmöle, P. (2022). Wege zu einer klimaneutralen Stahlerzeugung. Available online: https://vdeh.de/media/2022-06-09_luengen_schmoele_mgv_vdeh_public_final.pdf (accessed on 24 January 2023).

[32] Cavaliere, P., Perrone, A., Silvello, A., Stagnoli, P., & Duarte, P. (2022). Integration of Open Slag Bath Furnace with Direct Reduction Reactors for New-Generation Steelmaking. Metals, 12(2), 203. https://doi.org/10.3390/met12020203.

[33] Hölling, M.; Schäfers, H.; Gellert, S.; Grasenack, M.; Jürgens, L.; Tedjosantoso, N.; Schüttler, S. WiSaNo—Windstahl aus Norddeutschland. Technical Report. 2021. Available online: https://germany.arcelormittal.com/icc/arcelor/med/f53/f53689fc-e1fa-9718-60c5-e74064a585a0,11111111-1111-1111-1111-111111111111.pdf (accessed on 24 January 2023).

[34] Lechtenböhmer, S., & Fischedick, M. (2020). An integrated climate-industrial policy as the core of the European green deal (Vol. 2020). Wuppertal Institut für Klima, Umwelt, Energie. Available online : https://epub.wupperinst.org/frontdoor/deliver/index/docId/7483/file/7483_Climate-Industrial-Policy.pdf (accessed on 24 January 2023

Appendix

A1 – Supplementary Materials of publication II

Supplementary Materials of publication II 'Suer, J., Traverso, M., Ahrenhold, F.: Carbon footprint of scenarios towards climate-neutral steel according to ISO 14067. *Journal of Cleaner Production* (2021). https://10.1016/j.jclepro.2021.128588.'

Assumptions and Cut-off Criteria

All processes of the integrated site produce exactly the amount of product that is needed for the production of the declared unit. There is no purchase and sale of intermediate products. The internal accumulated scrap until the product hot-rolled coil is used completely in the basic oxygen furnace (BOF). For the scenarios injection of natural gas (NG) and H_2 in a blast furnace (BF) it is assumed that the emission factor [t CO_2/GJ_{BFG}] of the blast furnace gas (BFG) sinks compared to the conventional Base Case because the content of the BFG shifts from carbon to hydrogen. Thus, the emission reduction reported in the literature is included in the presented carbon footprint assessment. The calorific value of the BFG is assumed to be constant, which is a conservative approach, since the energy input increases for the considered scenarios. The heating value of the BFG affects the electricity and steam production in the power plant. For the scenarios use of hot briquetted iron (HBI) in a BF it is assumed that the chemical composition of the BFG is constant compared to the Base Case and so its specific emission factor and calorific value. The GHG reduction reported in the literature is included in the presented carbon footprint assessment by assuming a decreased BFG production. According to Griesser and Buergler (2019), the calorific value of the BFG increases up to 1.5% per 100 kg/t_{HM} HBI input. As a result, the made assumption considering a constant calorific value is conservative. The operation mode of the BF is assumed to be identically for the use of both NG- and H_2-based DRI, though different carbon contents of the DRI. One alternative may be that the carbon free H_2-based DRI is carbonised by process off-gases so that it gets the same carbon content as the NG-based DRI. There are three options in which iron feedstock is replaced by the HBI input in BF, namely lump ore, iron ore pellets, and sinter. At first, it is conservatively assumed that the HBI replaces iron ore pellets and lump ore but the amount of sinter is kept constant. This assumption is varied within the sensitivity analysis. The auxiliary material inputs like fluxes into the sintering plant, BF or BOF are kept constant within all scenarios. Consequently, the amount and the quality of produced slag are assumed to be constant as well in all scenarios. Especially in case of replacing sinter by HBI, which is presented within the sensitivity analysis, these assumptions are arguable.

Concerning the end-of-life approach, the collection, sorting, and processing (e.g., shredding) of scrap is neglected in this work. The recycling rate is assumed to be 95% following the assumption of Neugebauer and Finkbeiner (2012). The external scrap input *S* is 0.15 t/t_{HRC}.

The construction phase of facilities, machines, infrastructure can be neglected because their value must be spread along their life span and are consequently low within an LCA study (Klöpffer and Grahl, 2014). This statement is especially for the energy-intensive steel production valid, since the emissions of the plants aggregated over their life span, which is e.g. for a blast furnace about 15 to 20 years, exceeds the emissions caused by construction, infrastructure etc. by far.

Internal transport is also neglected because according to the WSA (2019) the impacts of fuel combustion for internal transport within an integrated steel site are about $2.4 \cdot 10^{-4}$kg CO_2/kg_{CS}. These emissions are about 0.01% of the total emissions and so negligible.

The raw materials iron ore, pellet, coke, coal, scrap, limestone, lime, and dolomite represent more than 95% (w/w) of the total tonnage of inputs, excluding water (WSA, 2017). These raw materials were all considered within this study. Moreover, the input of the emission-intensive alloying elements and in addition also less emission-intensive inputs like gravel, bauxite, graphite amongst others were considered. All energy-related inputs are included. Thus, the cut-off criteria are conform to those defined by the WSA (2011) so the sum of excluded material flows is below 5% of mass, energy, or environmental relevance.

GaBi Databases for secondary data

In **Table 1**, the used GaBi databases are listed.

Table 1: GaBi Databases for secondary data

Material/Energy Flows	GaBi Database (SP 40, year 2020)
Steel Production - Alloying Elements	
Aluminium	DE: Aluminium ingot mix
Calcium silicate	EU-28 Calcium silicate
Copper	DE: Copper mix (99.999% from electrolysis)
Ferro Chrome Mix	DE: Ferro chrome mix (60%)
Ferro Manganese Mix	ZA: Ferro-manganese mix (74-82%)
Ferro Molybdenum	GLO: Ferro molybdenum(70-90%)
Ferro Silicon	GLO: Ferro silicon mix (90% Si)
Ferro Vanadium	ZA: Ferro-Vanadium
Nickel	GLO: Nickel mix (99.9%)
Tin	GLO: Tin
Titanium	GLO: Titanium
Titanium dioxide (rutile)	EU-28: Titanium dioxide pigment
Steel Production - Material Flows	
Argon	DE: Argon (gaseous)
Bauxite	EU-28: Bauxite
Calcium hydroxide	DE: Calcium hydroxide
Cement	Cement Mixer (Worldsteel)

Compressed air	GLO: Compressed air 7 bar
Dolomite	DE: Dolomite (ground)
Graphite	DE: Synthetic Graphite (via Petrol coke)
Iron Ore	DE: Iron ore-mix
Iron Ore Pellets	DE: Pellet-feed-mix (import mix)
Landfill	DE: Landfill for inert matter (Steel)
Limestone	DE: Limestone ($CaCO_3$; washed)
Lubricant	DE: Lubricants at refinery
Magnesium	CN: Magnesium
Nitrogen	DE: Nitrogen (gaseous)
Oxygen	DE: Oxygen (gaseous)
Process Water	EU-28: Process water
Quicklime	DE: Lime (CaO; finelime)
Sodium Chloride	DE: Sodium chloride (rock salt)
Silica Sand	DE: Silica sand (Excavation and processing)
Water (deionised)	DE: Water (desalinated; deionised)
Water (from groundwater)	EU-28: Tap water from groundwater
Steel Production - Energy Flows	
District Heating	EU-28: District heating mix
Electricity	DE: Electricity grid mix
Hard coal mix	DE: Hard coal mix
Natural Gas	DE: Natural gas mix
Steam	DE: Process Steam from natural gas, 95%
Steel Production - Credit Material Flows	
Basic Oxygen Furnace Slag	DE: Lime (CaO; finelime)
	EU-28: Gravel 2/32
Benzene	DE: Benzene mix
Blast Furnace Slag	Cement Mixer (Worldsteel)
	EU-28: Gravel 2/32
	DE: Landfill for inert matter
Sulphur	DE: Sulphur (elemental) at refinery
Sulphuric Acid	DE: Sulphuric acid (96%)
Tar	EU-28: Bitumen at refinery
Hydrogen Production	
Electrolysis Process	GLO: Hydrogen (electrolysis, decentral)
Electricity for Electrolysis from	
Biomass	DE: Electricity from biomass (solid)
Biogas	DE: Electricity from biogas
Hydro	DE: Electricity from hydro power
Geothermal	DE: Electricity from geothermal
Photovoltaic	DE: Electricity from photovoltaic
Wind	DE: Electricity from wind power

For the most important processes concerning iron feedstock - iron ore, iron ore pellet -, energy related feedstock - hard coal, natural gas, electricity, steam -, and fluxes related feedstock - limestone, quicklime, and dolomite -, only German databases were used so that local representativeness is given. The modelling of hydrogen is also based exclusively on German renewable electricity mixes.

Carbon Footprint of hydrogen

The hydrogen is assumed to be produced via electrolysis driven by a German renewable electricity mix from the year 2018. The electricity mix is based on the study of the Environment Agency (Umweltbundesamt, 2019). The electrolysis process is taken from the GaBi database (SP40) "GLO: Hydrogen (electrolysis, decentral – for partly aggregation, open input electricity)". According to this database, 192 MJ electricity are required to produce 1 kg H_2, which is equivalent to an efficiency of 62.5% [energy unit hydrogen (LHV) / energy unit electricity].

The global warming potential (GWP) of hydrogen is 3.06 kg CO_2eq/kg, see **Table 2**. The share of the electrolysis process is 0.0473 kg CO_2eq/kg for H_2. About 3.01 kg CO_2eq/kg of H_2 result of the electricity demand by renewable energy.

Table 2: Global warming potential (GWP) of hydrogen. The hydrogen is produced via water electrolysis driven by a German renewable energy mix from year 2018.

Process step	GWP [kg CO_2eq/kg H_2]
Electricity supply by German renewable energy grid mix, year 2018[1] (192 MJ electricity/kg H_2)	3.01
Electrolysis according to GaBi database[2]	0.0473
Total	3.06

References

Griesser, A.; Buergler, Th (2019): Use of HBI in Blast Furnace. In BHM Berg-und Hüttenmännische Monatshefte 164 (7), pp. 267–273. DOI: 10.1007/s00501-019-0865-6.

Klöpffer, W.; Grahl, B. (2014): Life cycle assessment (LCA): a guide to best practice: John Wiley & Sons.

Neugebauer, S.; Finkbeiner, M. (2012): Ökobilanz nach ISO 14040/44 für das Multirecycling von Stahl. Available online at https://www.stahl-online.de/wp-content/uploads/2013/10/120621_Finkbeiner_Multi-Recycling_von_Stahl.pdf (accessed 05. January 2021)

Umweltbundesamt (2019): Erneuerbare Energien in Deutschland. Daten zur Entwicklung im Jahr 2018.

World Steel Association (2011): Life Cycle Assessment Methodology Report.

World Steel Association (2017): Life Cycle Inventory Methodology Report.

World Steel Association (2019): Life Cycle Inventory Study. 2019 data release.

[1] The German renewable energy mix is based on the study of the Environment Agency (Umweltbundesamt, 2019)

[2] GaBi database (SP40, year 2020): "GLO: Hydrogen (electrolysis, decentral – for partly aggregation, open input electricity)"

A2 – Supplementary Materials of publication III

Supplementary Materials of publication II 'Suer, J., Ahrenhold, F., Traverso, M.: Carbon Footprint and Energy Transformation Analysis of Steel Produced via a Direct Reduction Plant with an Integrated Electric Melting Unit. Journal of Sustainable Metallurgy (2022). Published August 2022. https://doi.org/10.1007/s40831-022-00585-x.'

Cut-off criteria and assumptions

The Worldsteel Association defined the following cut-off criteria for steel production [1]:

- All energetic input flows must be included.
- Each excluded material flow must not exceed 1% of mass, energy or environmental relevance for each process.
- The sum of the excluded material flows in the system must not exceed 5% of mass, energy or environmental relevance.

The raw materials iron ore, pellet, coke, coal, scrap, limestone, lime, and dolomite represent more than 95% of the total mass input (except water) [1]. These raw materials are all considered in this paper. Additionally, the emission-intensive alloying elements and also the less emission-intensive inputs like gravel, bauxite, graphite amongst others are included. All energy related inputs are considered. Thus, the cut-off criteria are conform to those defined by the Worldsteel Association [1]. The used GaBi databases [2] for secondary data are listed in table 1, table 2, table 3, table 4, and table 5.

Internal transport is neglected in this study. According to the Worldsteel Association the emissions from internal transport are 0.00024 kg CO_2/kg crude steel [3]. Thus these emissions can be cut-off according to the defined cut-off criteria. The construction phase of facilities, machines, and infrastructure of the integrated steel site are not considered. The emissions must be spread along their life span and are thus low compared to the process emissions of the energy-intensive steel production. However, the construction phase of the renewable electricity processes, which are especially for the H_2-Case of the study relevant, are included by the GaBi databases [2].

GaBi databases for secondary data

The used GaBi databases for secondary data are listed in the following. In table 1 the databases for the raw materials are listed; in table 2 the databases for the energy-related inputs; in table 3 the databases for the evaluation of the co-products; in table 4 the databases for the hydrogen production from electrolysis driven by a renewable electricity mix; in table 5 the databases for the input of alloying elements:

Table 1: GaBi databases for raw material inputs.

Material Flows	**GaBi Database (2021.1)**
Steel Production - Material Flows	
Argon	DE: Argon (gaseous)
Bauxite	EU-28: Bauxite
Calcium hydroxide	DE: Calcium hydroxide
Cement	EU-28: Cement (CEM I 42.5)
Compressed air	GLO: Compressed air 7 bar
Dolomite	DE: Dolomite (ground)
Graphite	DE: Synthetic Graphite (via Petrol coke)
Iron Ore	DE: Iron ore-mix
Iron Ore Pellets	DE: Pellet-feed-mix (import mix)
Landfill	DE: Landfill for inert matter (Steel)
Limestone	DE: Limestone ($CaCO_3$; washed)
Lubricant	DE: Lubricants at refinery
Magnesium	CN: Magnesium
Nitrogen	DE: Nitrogen (gaseous)
Oxygen	DE: Oxygen (gaseous)
Process Water	EU-28: Process water
Quicklime	DE: Lime (CaO; finelime)
Sodium Chloride	DE: Sodium chloride (rock salt)
Silica Sand	DE: Silica sand (Excavation and processing)
Water (deionised)	DE: Water (desalinated; deionised)
Water (from groundwater)	EU-28: Tap water from groundwater

Table 2: GaBi databases for energy-related inputs.

Material/Energy Flows	**GaBi Database (2021.1)**
Steel Production - Energy Flows	
District Heating	EU-28: District heating mix
Electricity	DE: Electricity grid mix
Hard coal mix	DE: Hard coal mix
Hydrogen	see Table 4
Natural Gas	DE: Natural gas mix
Steam	DE: Process Steam from natural gas, 95%

Table 3: GaBi databases for co-product evaluation.

Material/Energy Flows	**GaBi Database (2021.1)**
Steel Production – Co-products	
Benzene	DE: Benzene mix
Electricity	DE: Electricity mix
District heating	EU-28: District heating mix
Slag from basic oxygen furnace	DE: Lime (CaO; finelime) EU-28: Gravel 2/32
Slag from blast furnace and from melting unit	Cement Mixer (Worldsteel) EU-28: Gravel 2/32 DE: Landfill for inert matter
Sulphur	DE: Sulphur (elemental) at refinery
Tar	EU-28: Bitumen at refinery

Table 4: GaBi databases for hydrogen production.

Material/Energy Flows	GaBi Database (2021.1)
Hydrogen Production	
Electrolysis Process	GLO: Hydrogen (electrolysis, decentral)
Electricity for Electrolysis from	
Biomass	DE: Electricity from biomass (solid)
Biogas	DE: Electricity from biogas
Hydro	DE: Electricity from hydro power
Geothermal	DE: Electricity from geothermal
Photovoltaic	DE: Electricity from photovoltaic
Wind	DE: Electricity from wind power

Table 5: GaBi databases for alloying elements.

Material Flows	GaBi Database (2021.1)
Steel Production - Alloying Elements	
Aluminium	DE: Aluminium ingot mix
Calcium silicate	EU-28 Calcium silicate
Copper	DE: Copper mix (99.999% from electrolysis)
Ferro Chrome Mix	DE: Ferro chrome mix (60%)
Ferro Manganese Mix	ZA: Ferro-manganese mix (74-82%)
Ferro Molybdenum	GLO: Ferro molybdenum(70-90%)
Ferro Silicon	GLO: Ferro silicon mix (90% Si)
Ferro Vanadium	ZA: Ferro-Vanadium
Nickel	GLO: Nickel mix (99.9%)
Tin	GLO: Tin
Titanium	GLO: Titanium
Titanium dioxide (rutile)	EU-28: Titanium dioxide pigment

References

[1] World Steel Association (2017): Life Cycle Inventory Methodology Report.

[2] ©Sphera Solutions GmbH (2021): Gabi Database 2021.1

[3] World Steel Association (2019): Life Cycle Inventory Study. 2019 data release.