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Review

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

Julian Suer [1,2,*], Marzia Traverso [1] and Nils Jäger [2]

[1] Institute of Sustainability in Civil Engineering, RWTH Aachen University, 52074 Aachen, Germany
[2] Thyssenkrupp Steel Europe AG, 47166 Duisburg, Germany
* Correspondence: julian.suer@inab.rwth-aachen.de

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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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.

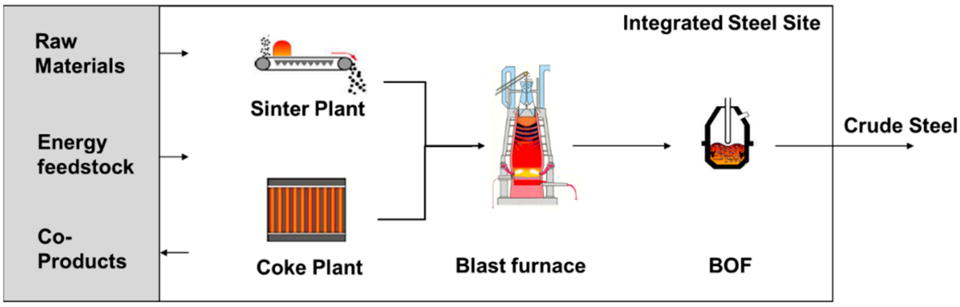

Figure 1. System boundary of an integrated steel site.

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].

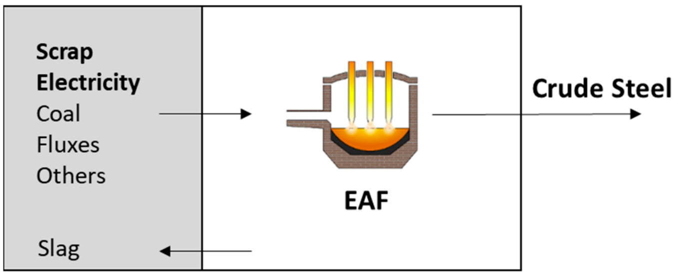

Figure 2. System boundary of an EAF-based recycling steel production.

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.

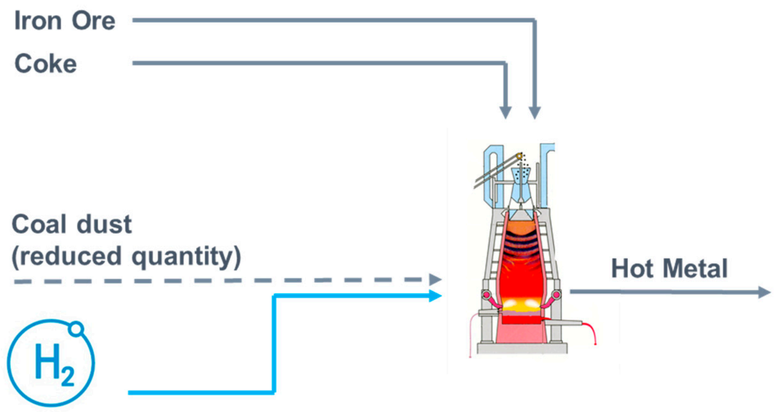

Figure 3. Injection of hydrogen into a blast furnace.

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.

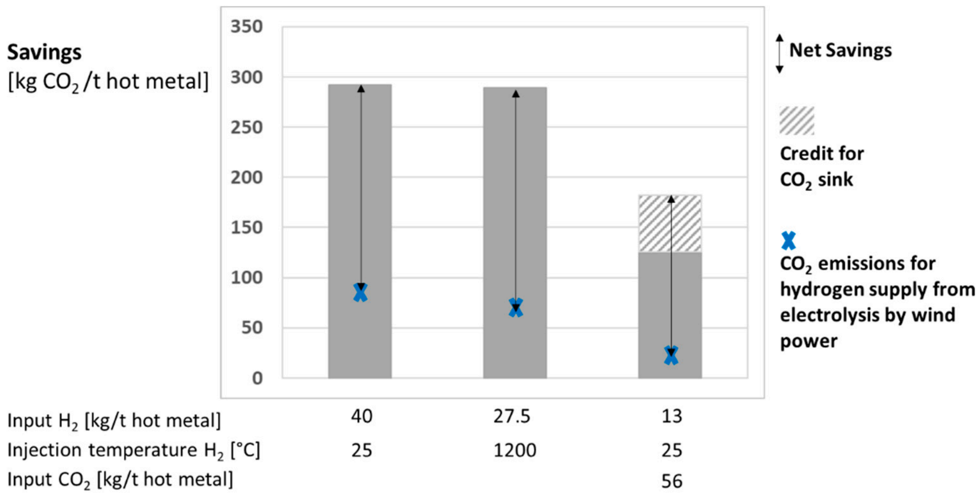

Figure 4. Carbon dioxide emission savings for injection of hydrogen into a blast furnace [52–55].

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].

$$Fe_2O_3 + 3\ H_2 = 2\ FE + 3H_2O \tag{2}$$

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.

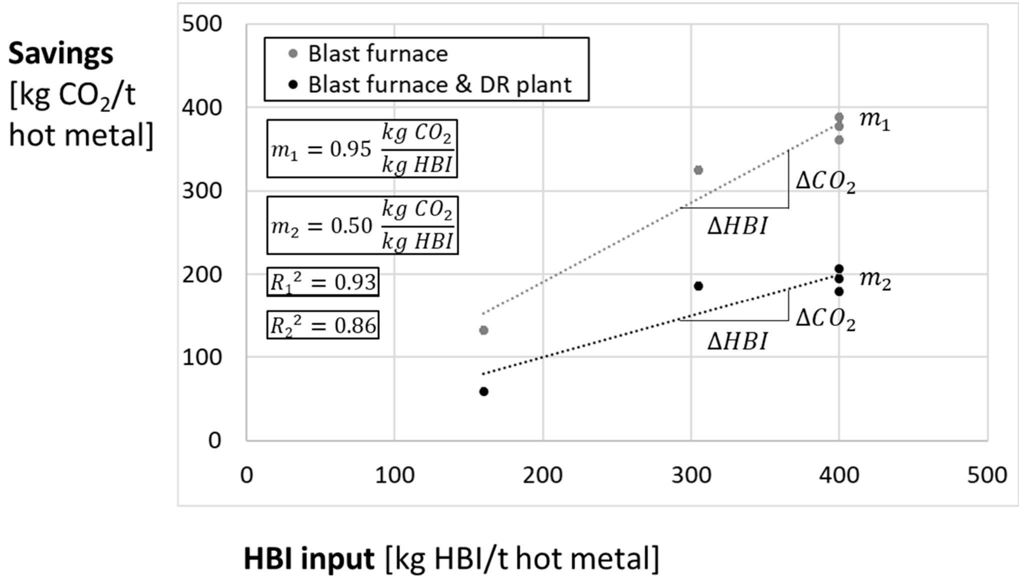

Figure 5. Carbon dioxide emission savings for HBI input in a blast furnace. The upper line describes the CO_2 savings of the blast furnace process. The lower one also includes the emissions of a natural gas-based DR plant [53,66,68–70].

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.

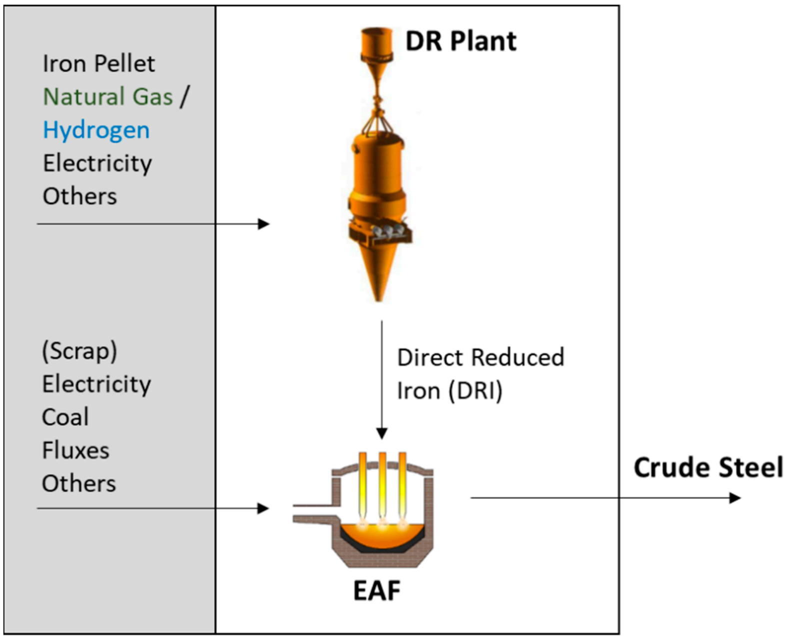

Figure 6. System boundary of crude steel production via a direct reduction plant (DR) and an electric arc furnace (EAF). Both, natural gas and hydrogen can be used as reducing agent within the DR plant.

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.

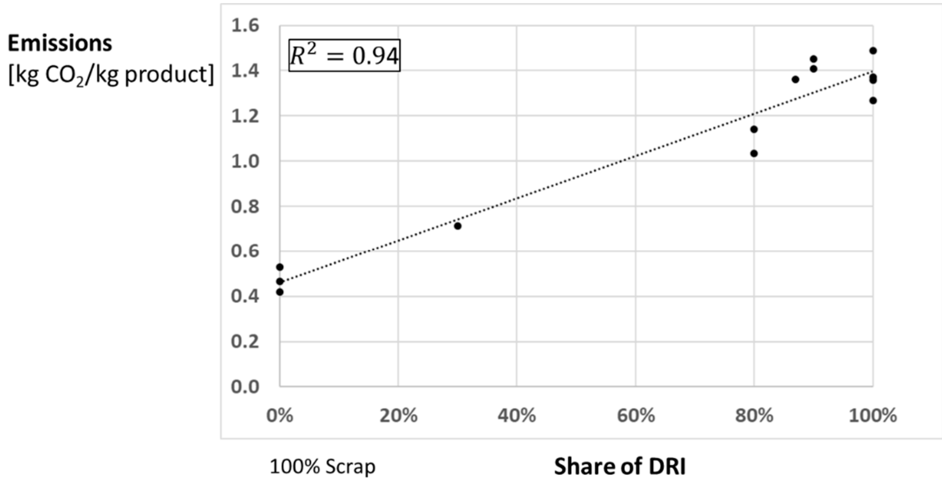

Figure 7. Carbon dioxide emissions of steel and hot-rolled coil production via a natural gas-based direct reduction (DR) plant combined with electrical melting. The emissions are presented as a function of a combined scrap and direct reduced iron (DRI) melting (kg DRI/(kg DRI + kg scrap)) [29,74–77,80,82].

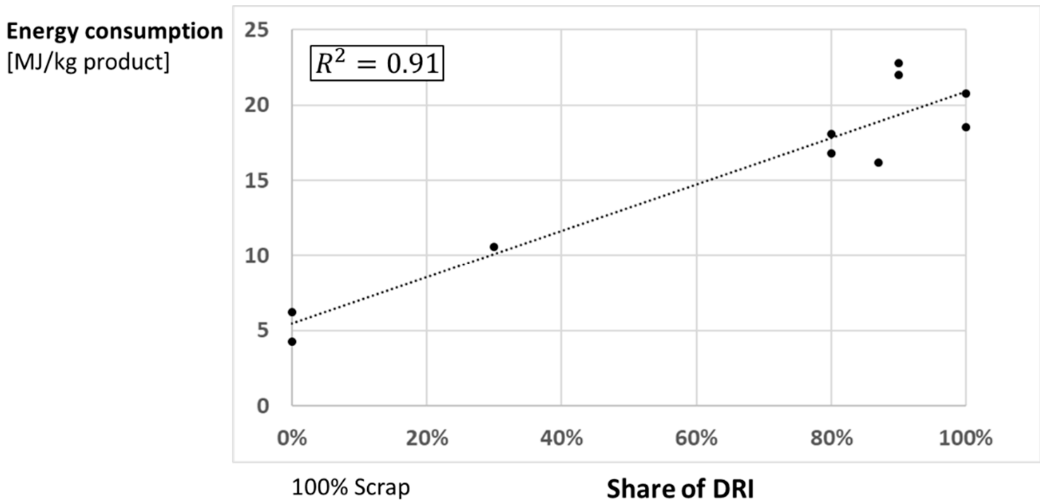

Figure 8. Energy consumption of steel and hot-rolled coil production via a natural gas-based direct reduction (DR) plant combined with electrical melting. The energy consumption is presented as a function of a combined scrap and direct reduced iron (DRI) melting (kg DRI/(kg DRI + kg scrap)) [74–77,80].

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].

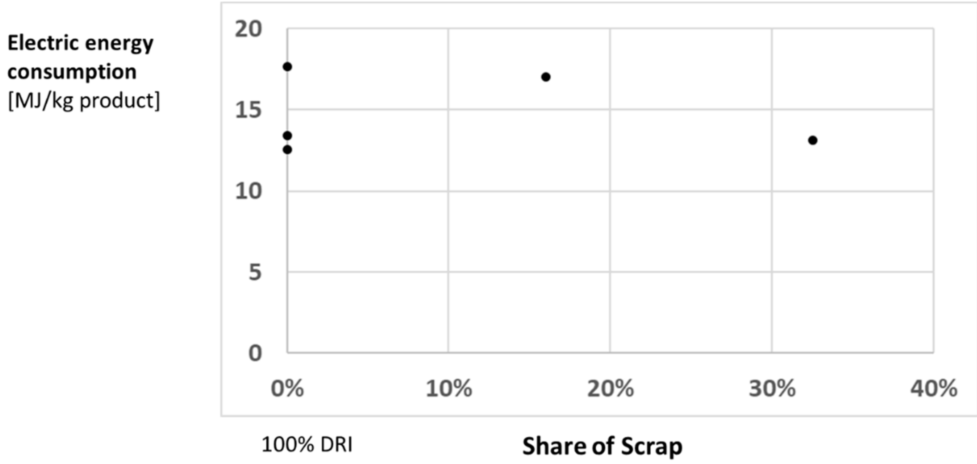

Figure 9. Electric energy consumption of steel and hot-rolled coil production via a hydrogen-based direct reduction (DR) plant combined with electrical melting. The energy consumption is presented as function of a combined scrap and direct reduced iron (DRI) melting (kg scrap/kg product) [74,82,83,86,87].

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]