H2FUTURE
Green Hydrogen

Deliverable D9.1

Report on exploitation of the results for the steel industry in EU28

v1.0

Funded by

Document Information

Deliverable Title	Report on exploitation of the results for the steel industry in EU28
Number of the Deliverable	D9.1
WP/Task related	[WP9 / T9.1, 9.2]
Distribution/Confidentiality	PU Public
Date of Delivery	[28-01-2021]
Status and Version	Version 1.0
Number of Pages	52 pages
Person Responsible for Document	Katharina Rechberger – K1-MET GmbH
Author(s)	Amaia Sasiain Conde, Katharina Rechberger – K1-MET GmbH
Reviewers	Hermann Wolfmeir, Chris Harris – voestalpine Stahl GmbH Marcel Weeda, TNO

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 735503. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY.

Revision History

Version	Date	Author / Reviewer	Notes
0.1	09/12/2020	A. Sasiain, K. Rechberger	Initial draft
0.2	15/12/2020	H. Wolfmeir, C. Harris	Review
0.3	18/01/2021	M. Weeda	Review
1.0	29/01/2021	A. Sasiain, K. Rechberger	Final version

Executive Summary

This study was conducted as part of Task 9.1 & 9.2 and analyses the transition from coal/coke-based towards hydrogen-based steel production including the production of green hydrogen via PEM-electrolysis.

The report encompasses a techno-economic analysis of the hydrogen-based crude steel production route, alongside the current production processes, focussing on the scaling and replication of the hydrogen electrolytic process for the steel industry.

Three different production routes were considered for the evaluation of the prospective development pathways of the steel industry towards a carbon free steel production: (I) the blast furnace route and the direct reduction with (II) natural gas and (III) hydrogen. The blast furnace route was considered as the reference technology for further calculations and the natural gas-based direct reduction as the bridge technology between the BF/BOF and hydrogen-based route, which is operated almost without the utilization of carbonaceous fossil sources. Nevertheless, to obtain a CO_2-lean steel production, the so-called “green hydrogen”; which is used as reducing gas for the production of crude steel must be generated from renewable energy, for example, via the electrolysis of water, one the most promising technology for green hydrogen production.

The analysis is based on comprehensive mass- and energy balances of those production processes followed by CO_2-balances. An economic assessment of hydrogen-based production enables the evaluation of possible scenarios for the future of steelmaking and their corresponding impacts, analysing the future demand of hydrogen and subsequently electricity for the conversion to carbon-lean processes. The goal is to determine under which technical and economic conditions the production of steel through the hydrogen route becomes a feasible solution for the steel industry.

Hydrogen-based steelmaking in combination with the production of hydrogen by PEM electrolysis is identified as suitable technology to reach the goals of a CO_2-reduction of 80-95 % if the process is fully operated with renewable electricity. Therefore, an additional energy demand of 340 TWh for EU 28 arises if steel currently produced by the BF/BOF route is transferred to hydrogen-based steelmaking. Under current price conditions, the overall production costs via the DR(H_2)/EAF route are ~35 % higher than for the BF/BOF or DR(CH_4)/EAF route. In conclusion, for an economically viable steel production based on hydrogen, low electricity prices, an overall decrease of electrolyzer costs and, contrarily, higher prices for CO_2-emissions are essential.

Table of Contents

List of Figures

List of Tables

1 Introduction

Work Package 9 (WP 9) of H2FUTURE project has the objective of quantifying and benchmarking the technical, economic, environmental and grid related performance of a 6 MW polymer electrolyte membrane (PEM) electrolysis-based demo-plant for hydrogen production and to design scaling and replication scenarios in potentially interested EU 28 Member states for the steel and fertilizer industry based on the experimental data gathered during the operation of the demo-plant. In order to accelerate the deployment of the demonstrated solution in the steel industry, the proposal of recommendations for regulatory changes are as well among the goals of WP9.

Four working areas and related tasks have been defined to cover the impacts of the project results and exploitation:

- Task 9.1.: Performances of the electrolyzer system
- Task 9.2.: Scaling and replication of the H_2 generation electrolytic process in EU 28 for the steel industry
- Task 9.3.: Scaling and replication of the H_2 electrolytic process for the fertilizer value chain in EU 28
- Task 9.4.: Implementation of exploitation measures for the steel industry core market
- Task 9.5.: Implementation of exploitation measures for the fertilizer core market
- Task 9.6.: Final recommendations to regulatory bodies

1.1 Background

As part of the H2FUTURE project a 6 MW polymer electrolyte membrane (PEM) electrolysis system is installed at the steelworks in Linz, Austria. After the pilot plant has been commissioned, the electrolyzer is operated during a demonstration period, which is split into five pilot tests and a period of quasi-commercial operation. The aim of the demonstration is to assess the performance characteristics of the PEM electrolyzer and to determine whether the installation is able to produce green hydrogen from renewable electricity while using timely power price opportunities and to provide grid services (i.e. ancillary services) in order to attract additional revenue.

Next to the experimental program, replicability of the experimental results on a larger scale in EU28 for the steel industry and other hydrogen-intensive industries is studied during the project. Finally, policy and regulatory recommendations are made in order to facilitate deployment in the steel and fertilizer industry, with low CO_2 hydrogen streams also being provided by electrolyzer units using renewable electricity.

Due to several delays on the installation of the electrolyzer within the H2FUTURE project, (as explained in the second periodic report), the pilot tests started at the end of the first quarter 2020. Results of plant operation were not sufficiently available for the calculations on the exploitation of the steel industry which were performed for this report. Therefore, the performance of the electrolyzer system used for the calculations for the scaling and replication of the results in EU 28 for the steel industry, is the performance expected described in the project proposal. Thus, the figures used for the calculations were: 75% as the overall electrolysis system efficiency (based on the higher heating value of hydrogen, 3.54 kWh/m^3) and a hydrogen production of 1,200 m^3/h. As soon as the demonstration period comes to its end, and the performance figures are available, the expected values used for the calculations will be substituted by the results obtained from the tests.

1.2 Scope of the Document

Work Package 9 (WP9) has the objective of quantifying and benchmarking the technical, economic, environmental and grid related performance of the tested system and to design scaling and replication scenarios in potentially interested EU28 Member states for the steel and fertilizer industry based on the experimental data gathered during operation of the demo-plant. In order to accelerate the deployment of the demonstrated solution in the steel industry the proposal of recommendations for regulatory changes are as well among the goals of WP9.

The scope of this document, deliverable D9.1, is to evaluate the possibilities and constraints of the implementation of green hydrogen produced by PEM-electrolysis in the steel production chain. Therefore, the options of exploiting H2-generation to the steel industry in EU28 should be discussed. After providing an overview about the current situation of the European steel production, the transition from coal/coke-based towards hydrogen-based steel production including the production of green hydrogen via PEM-electrolysis is analysed. The evaluation is based on comprehensive mass- and energy balances of the different steel production processes followed by CO_2-balances as well as an economic evaluation of hydrogen-based steelmaking.

Notations, Abbreviations and Acronyms

Table 1: Acronyms list

BF	Blast Furnace
BOF	Basic Oxygen Furnace
CAPEX	Capital Expenditures
CDRI	Cold Direct Reduced Iron
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CDA	Carbon Direct Avoidance
COG	Coke Oven Gas
CS	Crude Steel
DR	Direct Reduction
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
GA	Grant Agreement
HBI	Hot Briquetted Iron
HDRI	Hot Direct Reduced Iron
NG	Natural Gas
OPEX	Operational Expenditures
PCI	Pulverised Coal Injection
PEM	Polymer Electrolyte Membrane / Proton Exchange Membrane
SCU	Smart Carbon Usage
TSO	Transmission System Operator
WACC	Weighted Average Cost of Capital
WP	Work Package

2 Scaling and replication of the H_2 electrolytic process for the steel industry

2.1 Current status of the steel industry in EU28

In 2019 global crude steel production reached 1.87 billion tonnes, 8.5% of which were produced in the European Union [1]. Nowadays, crude steel production in Europe is almost entirely divided between steel produced via the basic oxygen furnace route in combination with blast furnace and the mainly scrap-based electric arc furnace (EAF) route, representing respectively 58.5 % and 41.5 % of the EU28 steel production [2].

Despite the existence of other possible steelmaking processes as for example the gas-based direct reduction route or the coal-based smelting reduction route (Figure 1), it should be remarked that these processes cannot achieve the production capacity of large blast furnaces.

The global production amount of direct reduced iron (DRI) is rated on 180 million tonnes per year in 2019, thus representing a minor part of the overall steel production. About 50 % of the DRI is produced in Middle East/North Africa, followed by Asia/Oceania (34 %) [3]. This limitation to specific regions originates from the availability of cheap natural or reducing gas which enables an economic viable production of DRI.

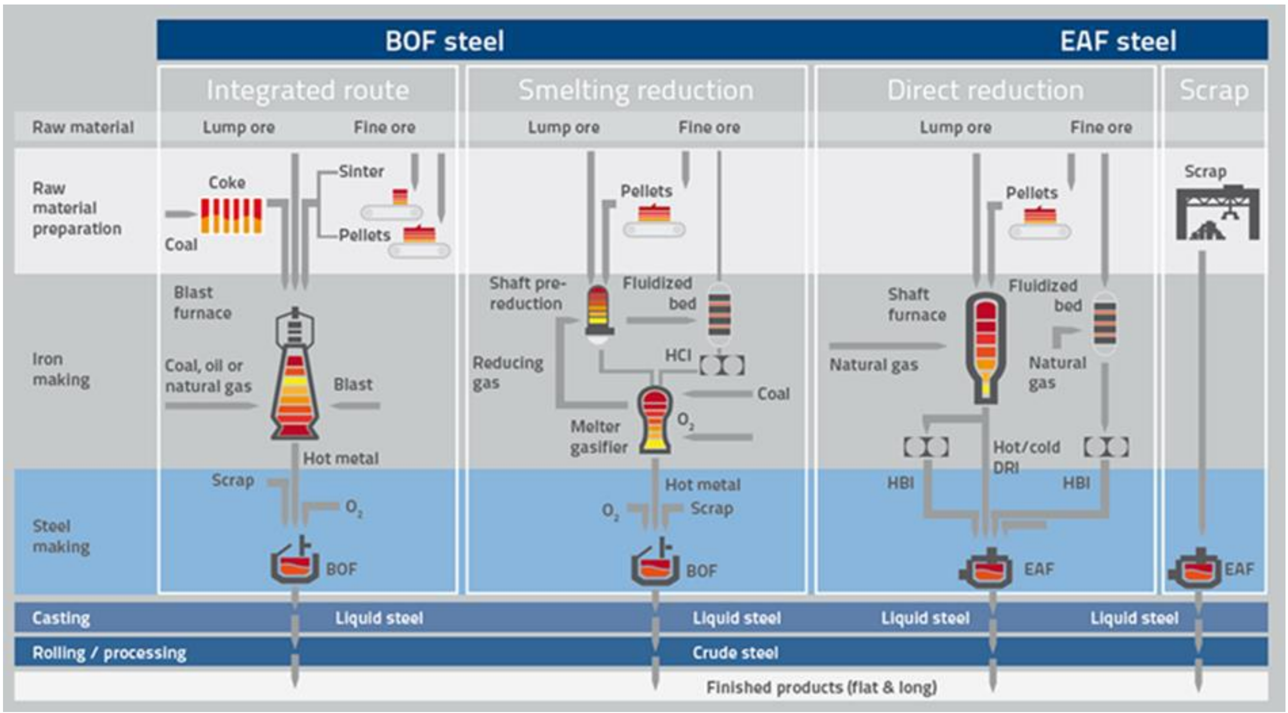

Figure 1: Overview of iron and steel making routes [4]

The production of steel from iron ores is closely linked to the element carbon and thus highly dependent on fossil fuels. The carbon is used as reducing agent and energy source resulting in large amounts of CO_2. Considering the decrease of CO_2-intensity of the power sector as well as the increase in availability and use of scrap, the maximum CO_2-reduction potential attainable between 2010-2050 with the actual production routes presented in Figure 1 is about 15% [4]. Despite the lower carbon footprint of the scrap-EAF route, natural iron sources as raw material will be still required in the future due to the limited availability of scrap of sufficient quality. The ambition of the steel sector is to reduce the CO_2-emissions by 80-95 % in 2050 compared to 1990 levels [5]. Reaching this goal will not be achievable without the use of the so-called “breakthrough technologies”.

2.1.1 Size of the steel industry

The European steel industry produced 167.7 million tonnes [2] of steel in 2018 at more than 500 production sites across 22 EU member states [6]. Since 2009, the steel production amounts range between 140 and 178 million tonnes [2]. Figure 2 depicts the EU countries shown by relative size of crude steel production.

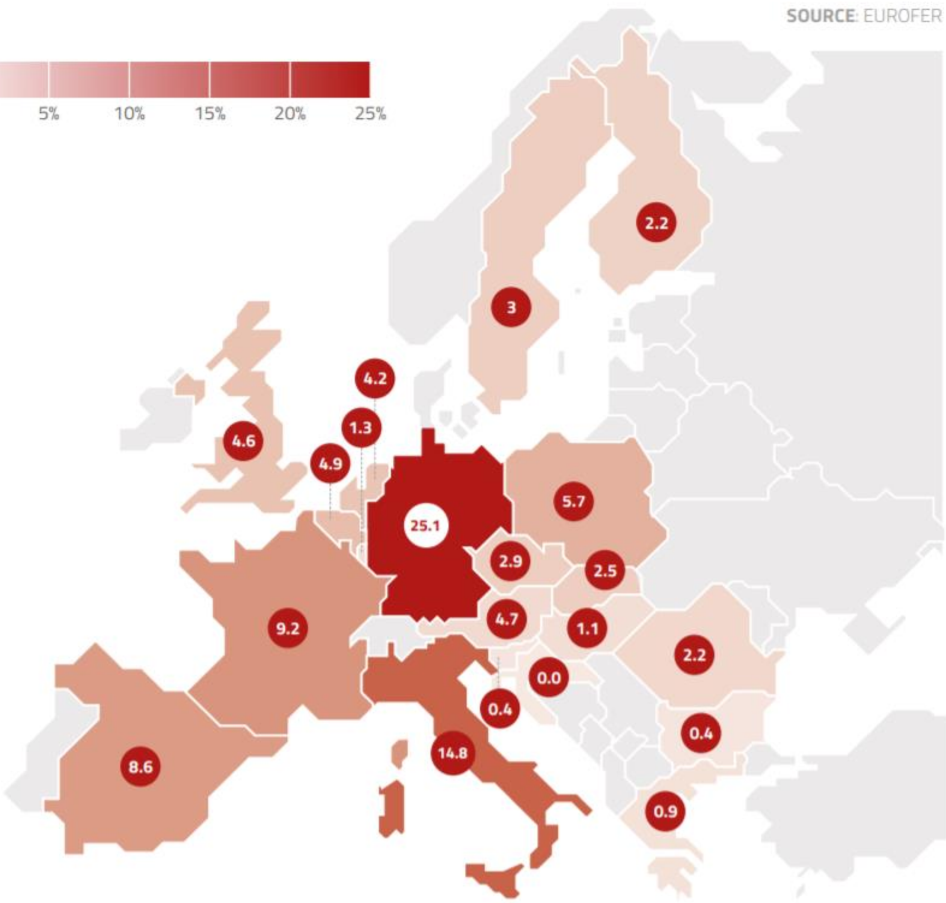

Figure 2: Relative size of crude steel production in the EU tonnes [1]

Table 2 shows the crude steel production in Europe for the year 2018 together with the production facilities available in every European country. Furthermore, the amounts of crude steel produced by the different production routes are important for the evaluation of CO_2-reduction potentials (see Figure 3). The top five countries with the highest potential for a reduction in CO_2-emissions originating from the integrated route (BF/BOF) seems to be Germany, Italy, France, UK and Austria. This is because they are among the largest crude steel producers in EU 28 and at the same time they operate the largest number and amount of steel produced by blast furnaces in Europe.

Table 2: Total production of crude steel and crude steel production assets across EU28

EU-28 Countries	Number of BF & BOF [7]	Number of EAF [7]	CS production BOF [Mt] [2]	CS production EAF [Mt] [2]	CS production total [Mt] [2]
Austria	5	3	6.2	0.7	6.9
Belgium	2	5	5.4	2.6	8.0
Bulgaria		2		0.7	0.7
Croatia		2		0.1	0.1
Czech Republic	5(A)	3	4.7	0.2	4.9
Finland	2	3	2.8	1.4	4.1
France	5	14	10.5	4.9	15.4
Germany	14(B)	22	29.7	12.7	42.4
Greece		5		1.5	1.5
Hungary	2	1	1.7	0.3	2.0
Italy	4	33	4.5	20.0	24.5
Latvia					
Luxembourg		2		2.2	2.2
Netherlands	2		6.8		6.8
Poland	3	11	5.4	4.8	10.2
Portugal				2.2	2.2
Romania	2	4	2.2	1.4	3.6
Slovakia	2	1	4.8	0.4	5.2
Slovenia		3		0.7	0.7
Spain	3(C)	23	4.9	9.4	14.3
Sweden	3	6	2.8	1.8	4.7
United Kingdom	5	5	5.7	1.6	7.3
EU28	**59**	**148**	**98.1**	**69.6**	**167.7**

(A) Three from this 5 BF&BOF are only blast furnaces (they are not accompanied by any BOF)

(B) One from this 14 BF&BOF is only a basic oxygen furnace (it is not accompanied by any BF)

(C) One from this 3 BF&BOF is only a basic oxygen furnace (it is not accompanied by any BF)

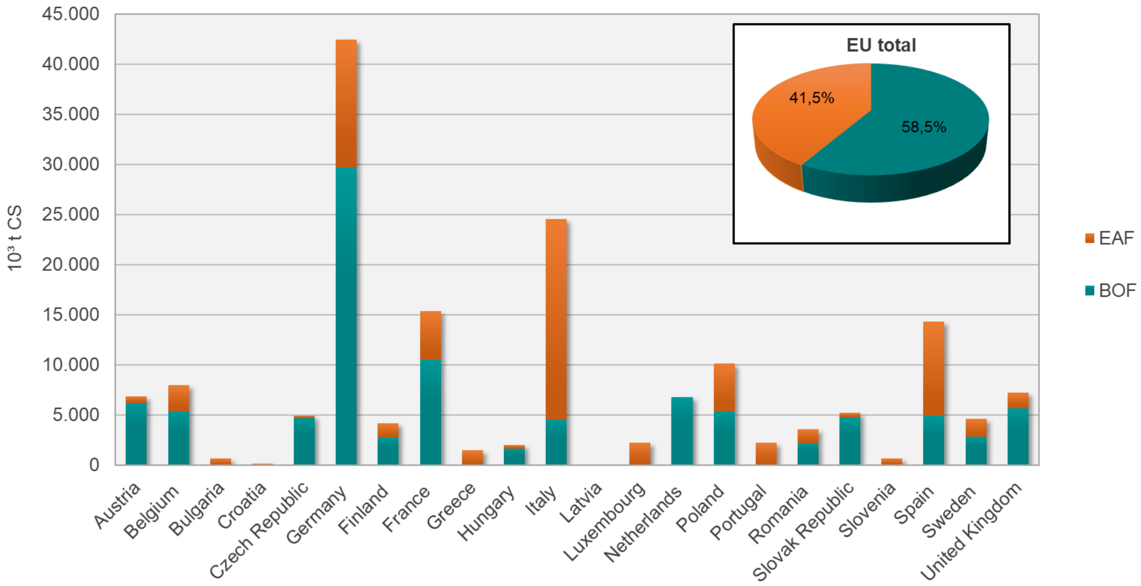

Figure 3: Current steel production amounts depending on process [2]

2.1.2 Selection of production processes

For achieving substantial CO_2-reduction rates in the steel sector, there are two main technological pathways: 1) Smart Carbon Usage (SCU) including process integrated measures for a decreased use of carbon in existing processes and utilization of CO_2 as a raw material for chemical conversion (CCU), optionally combined with carbon capture and storage (CCS). 2) Replacement of carbon by renewable electricity and/or fossil-free reductants in order to directly avoid CO_2-emissions (Carbon Direct Avoidance – CDA) [5].

CDA-processes can mainly be split into hydrogen-based and electricity-based reduction processes. Electrical power-based iron reduction technologies use electricity to produce steel by means of iron ore electrolysis at different temperature levels (low temperature iron electrowinning, high-temperature pyro-electrolysis) [8], [9]. They provide high potentials for CO_2-reduction of up to 95 % if 100 % renewable electricity is used [10]. These processes are currently under development. The same also applies for processes replacing carbon-containing reducing agents by hydrogen either in solid state (direct reduction) or in liquid state (plasma smelting reduction). Hydrogen plasma smelting reduction directly converts iron ore fines to liquid steel via hydrogen in ionized form. Hydrogen plasma is used for the reduction of the oxides and simultaneously provides heat for melting the metallic iron [11].

Direct reduction processes with natural gas (DR(CH_4)) as one of the state-of-the-art steelmaking technologies, can provide the basis for the introduction of hydrogen. Existing DR(CH_4)processes already operate with a hydrogen containing syngas, which is previously produced by the reforming of natural gas. Based on this process concept, additional amounts of hydrogen can be implemented in order to achieve a further CO_2-reduction.

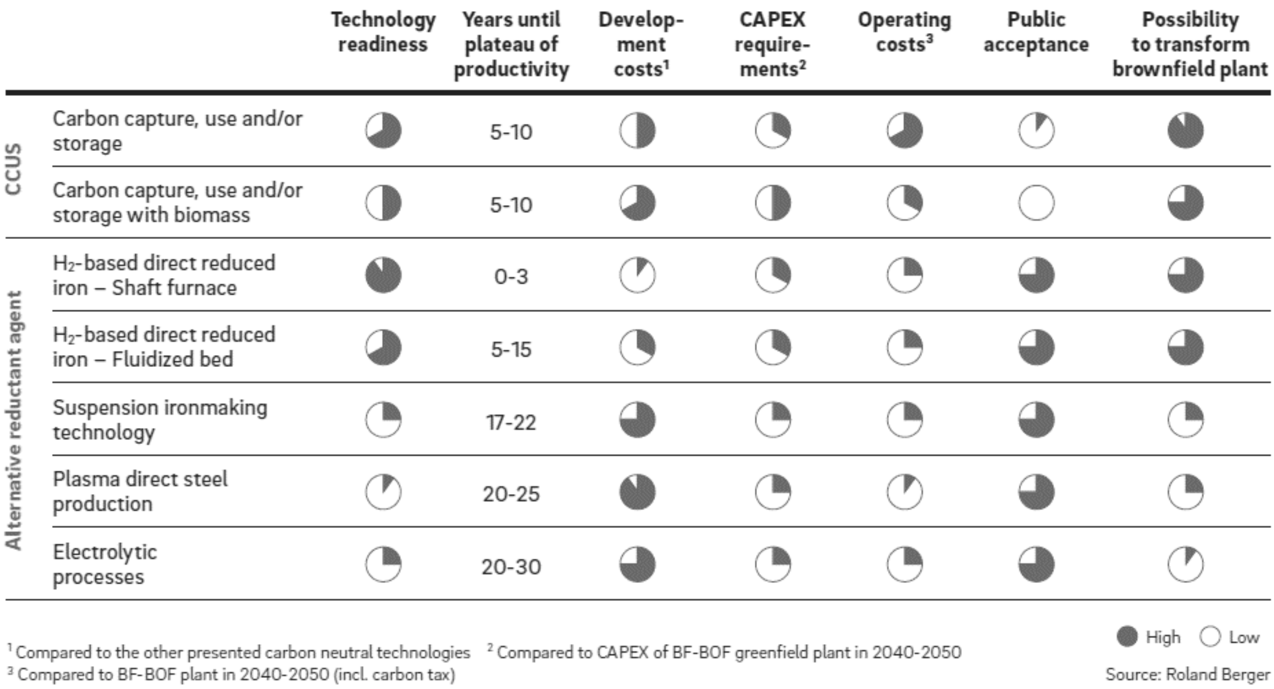

Figure 4: Comparison of CO_2-mitigation technologies [12]

The different technologies for a CO_2-reduced steel production vary significantly in their level of technology readiness, effort for the required development, investment and operation costs as well as the applicability to existing plants (see Figure 4). Hydrogen-based direct reduction is rated as one of the most developed technologies in combination with low or modest efforts for a further development, CAPEX and OPEX. Therefore, this route can currently be considered to have the best prospects for future low carbon steelmaking. Another important issue is that the DR(CH_4)/EAF process which provides the basis for this transition is already state of the art and hydrogen can be gradually implemented to the process. Furthermore, voestalpine is already running a MIDREX DR-plant in Corpus Christi, Texas since 2017 and thus already gained detailed process knowledge which is important for further considerations regarding hydrogen. Based on these outcomes, the hydrogen-based direct reduction process (DR(H_2)/EAF) was selected as low-carbon steelmaking alternative for the future in the following calculations and evaluations.

In order to evaluate the possible development of the pathways of the steel industry towards a carbon-lean steel production, the following three different production routes were taken into account for the subsequent considerations: (I) BF/BOF, (II) DR(CH_4)/EAF and (III) DR(H_2)/EAF. The BF/BOF route as state-of-the art represents the reference technology, which is the basis for further calculations. As the transition to a carbon-lean steelmaking also requires a change in steelmaking technology, the DR(CH_4)/EAF process (natural gas-based direct reduction) is also evaluated as a bridge technology between the BF/BOF and hydrogen-based route.

Simulations of these three different processes were carried out to define and calculate scenarios for future steelmaking and their corresponding impacts. Energy and mass balances given in literature were screened and used as input and for validation of the simulation models. The models were set up in a process simulation platform using the m.SIMTOP® model library for metallurgical processes which has been developed by Primetals Technologies and voestalpine in recent years [13].

To determine the production costs through the hydrogen-direct reduction route and compare it with the natural gas-based direct reduction and the blast furnace process, an integral evaluation of the entire process chain including evaluation of the energy and reactants consumption, the CO_2-emissions, etc. must be carried out. This approach is required since the BF/BOF and the DR/EAF are two entirely different processes and there is currently no direct reduction process operated solely with hydrogen as a reference.

2.1.3 Current production routes

2.1.3.1 BF/BOF route: reference technology - state of the art

The blast furnace together with the basic oxygen furnace represents the reference steel production technology. In the integrated route (BF/BOF), iron ores, pellets, and sinter are reduced in the BF using predominantly coal and coke. The reducing gas (mainly CO) is generated by the reaction of carbon from coke or coal with the oxygen from the hot blast and via direct oxygen removal from the iron ore. The reduced liquid iron is called hot metal. During the transition to the liquid phase, impurities are separated from the hot metal by a liquid slag. The hot metal is then charged to the BOF where O_2 is injected to remove remaining unwanted elements like phosphorous and the residual carbon. Scrap is used to control the temperature of the exothermic reactions taking place in the BOF process. Sometimes, DRI or HBI is also added into the BOF.

Figure 5 shows a simplified version of the flowsheet of a standard steel mill plant, including one blast furnace, one converter, a coking and a sinter plant and a power plant. To create an illustrative BF/BOF model, different figures were taken from literature in order to build energy and mass balances representative for the entire European industry. Afterwards, those values were computationally tested through several simulations. For this purpose the software gProms was used. A process model was developed using the input and output values from mass balances specified in the literature and the BAT-document. The results of the model were also verified with these data. The upstream processes, as coke and sinter production, were as well considered in order to have a wider overview of the process in terms of CO_2-emissions, energy utilization, and crude steel production rate. The main input parameters as well as the obtained results of the mass balance are summarized in Table 3.

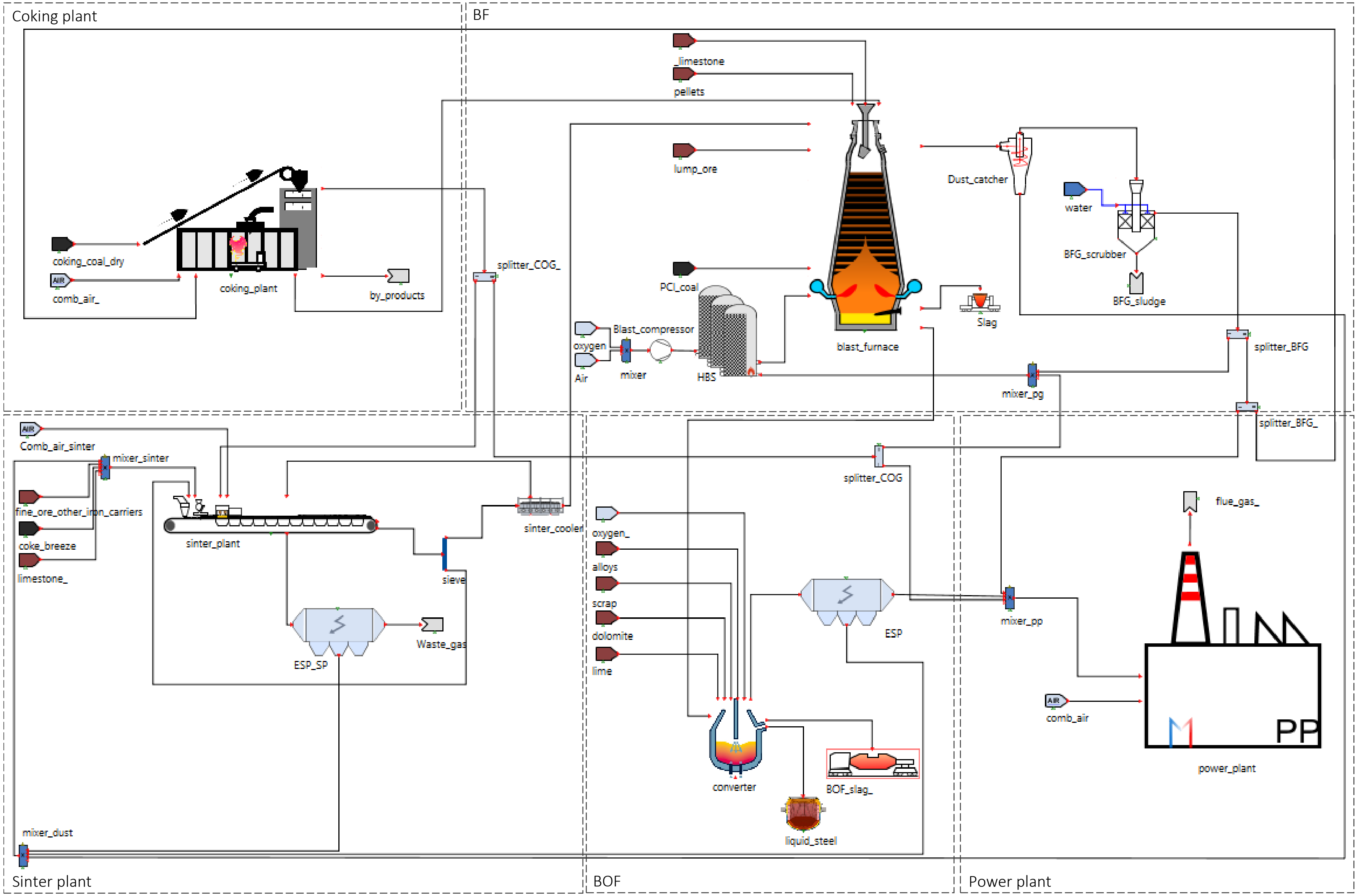

Figure 5: Process scheme and system boundaries of BF/BOF process

Table 3: Results from the energy and mass balance calculations BF/BOF route

Coking Plant					
input	coking coal dry	1290.9	kg/t coke	394.0	kg/t CS
	process gases	3626.9	MJ/t coke	1106.9	MJ/t CS
output	coke			305.2	kg/t CS
	by-products	91.2	kg/t coke	27.8	kg/t CS
	process gases	8699.2	MJ/t coke	2654.9	MJ/t CS
Sinter Plant					
input	fine ore + other iron carriers	952.9	kg/t sinter	785.9	kg/t CS
	coke breeze	48.5	kg/t sinter	40.0	kg/t CS
	limestone	145.5	kg/t sinter	120.0	kg/t CS
	process gases (e.g. COG)	69.6	MJ/t sinter	57.4	MJ/t CS
output	sinter			824.8	kg/t CS
Blast Furnace					
input	sinter	1013.1	kg/t HM	824.8	kg/t CS
	lump ore	180.0	kg/t HM	146.5	kg/t CS
	pellets	358.0	kg/t HM	291.4	kg/t CS
	limestone	30.0	kg/t HM	24.4	kg/t CS
	coke	374.9	kg/t HM	305.2	kg/t CS
	PCI coal	161.6	kg/t HM	122.1	kg/t CS
	process gases (e.g. COG, BFG)	2178.2	MJ/t HM	1773.2	MJ/t CS
	oxygen	12.3	m^3_{STP}/t HM	10.0	m^3_{STP}/t CS
output	hot metal			814.1	kg/t CS
	BF-slag	251.0	kg/t HM	204.3	kg/t CS
	process gases	5589.3	MJ/t HM	4550.0	MJ/t CS
Basic Oxygen Furnace					
input	hot metal			814.1	kg/t CS
	scrap			270.7	kg/t CS
	lime			37.4	kg/t CS
	dolomite			23.6	kg/t CS
	alloys			17.0	kg/t CS
	oxygen			51.2	m^3_{STP}/t CS
output	liquid steel			1000.0	kg/t CS
	BOF-slag			106.9	kg/t CS
	process gases			539.6	MJ/t CS

In the existing steel mills, which predominantly comprise of a BF/BOF system, a large part of the off gases produced in the blast furnace and basic oxygen furnace are recycled for various purposes: (I) the production of electricity in the steel mill, (II) its reuse in the blast furnace to heat the hot blast,

(III) its reuse in the coking plant and (IV) its utilization in the hot strip mill or other downstream processes. When turning into a low carbon steel industry, point (I) and (IV) will be highly important, as those gases will no longer be available when using other steel production processes, and thus this energetic demand has to be covered by renewables.

2.1.3.2 DR(CH_4)/EAF: bridge technology

Direct reduction with natural gas in conjunction with EAF belongs to the state of the art of the steel producing technologies. Additionally, it provides the possibility for injecting hydrogen as reducing agent as well as to run the process only with hydrogen. Therefore, this production process was chosen as bridge technology for the transition of current coal-based production towards a carbon-lean steel production. As this process must also be taken into account for the analysis of CO_2-, energy-balances and cost structure, a simulation model was developed which serves as the basis for these analyses (see Figure 6).

DR-processes operate without any liquid phase unlike the BF. Oxygen is removed by reacting with hot reducing gas in the DR-shaft furnace. The hot DRI can either be fed right into the EAF or it can be briquetted to hot briquetted iron (HBI) for selling purposes or cooled and used as cold DRI (CDRI).

Natural Gas acts as source for the reducing agent. To generate the gases required for the reduction (mainly CO and H_2), the natural gas must previously be reformed to syngas following simultaneously the reaction of steam methane and dry reforming (see Eq. 1, 2). In the case of the MIDREX® process, the syngas contains about 55 % of hydrogen and 35 % of carbon monoxide. Then, the oxygen from the iron ore reacts in the DR-shaft with CO and H_2 at elevated temperatures to produce metallic iron while releasing CO_2 and H_2O, according to Eq. (3) and (4).

$$CH_4 + CO_2 \rightarrow 2\ CO + 2\ H_2 \quad (1)$$

$$CH_4 + H_2O \rightarrow CO + 3\ H_2 \quad (2)$$

$$Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe + 3\ H_2O \quad (3)$$

$$Fe_2O_3 + 3\ CO \rightarrow 2Fe + 3\ CO_2 \quad (4)$$

The remaining off-gas from the shaft furnace, the so-called “top gas” rich in CO_2 and H_2O is treated in a gas scrubber, where water is partly condensed and the dust is removed. Around two thirds of those processed gases return as feed inlet to the reformer, once blended with fresh natural gas. The remaining part is mixed as well with natural gas and combusted with air to serve as heating source for the reformer. This combusted gas is the major emission source of the DR-process.

Unlike hot metal, DRI still contains residual oxygen and other unwanted materials from the iron ores which have to be removed in the next stage, the EAF. The DRI or HBI is melted in the EAF, to produce liquid crude steel. Scrap may be added to improve the performance of the EAF and for cost optimization.

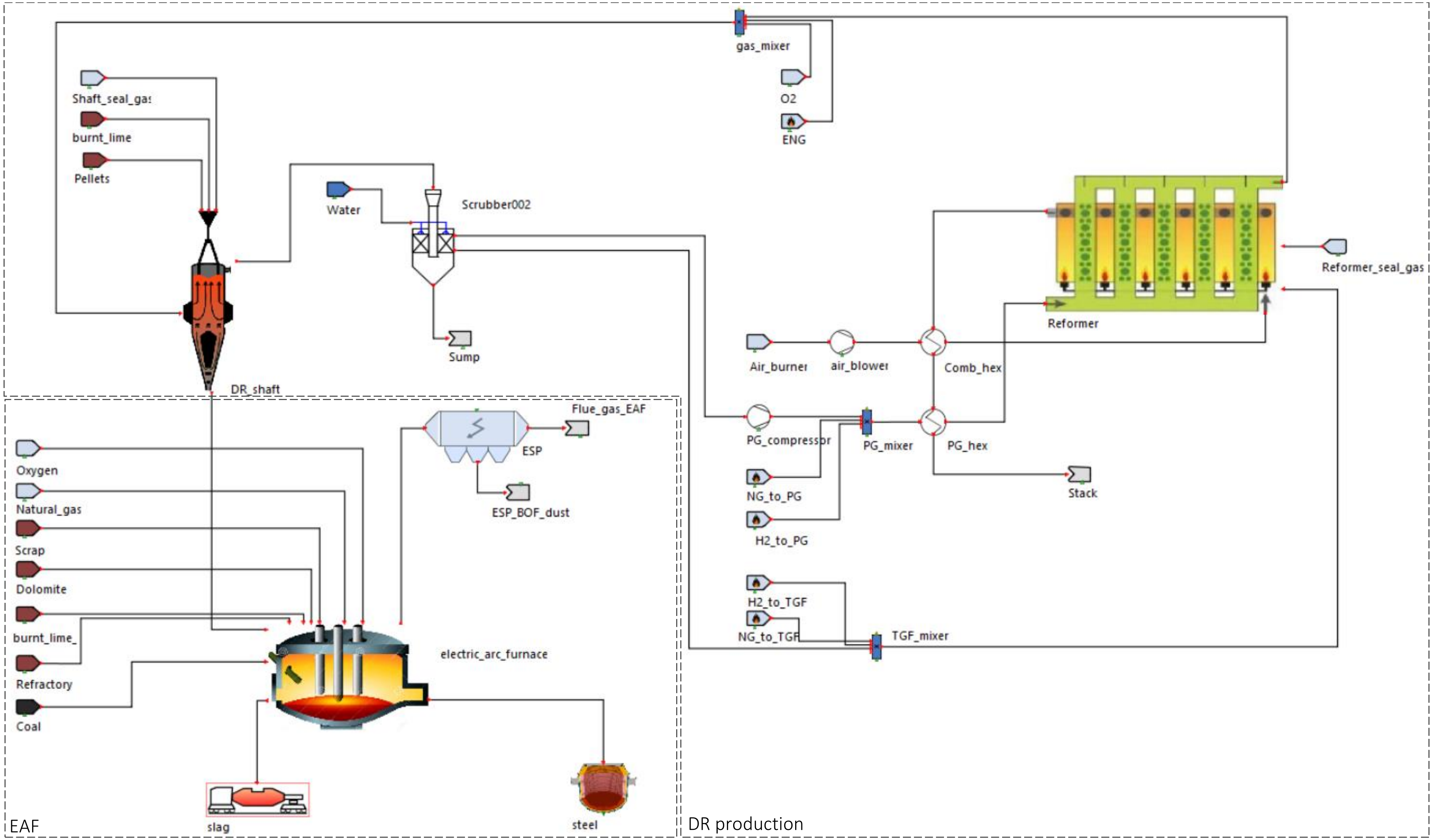

Figure 6: Process scheme and system boundaries of DR(CH4)/EAF process

The DRI carbon content is of critical importance when used in an electric arc furnace to complete the metallization of the iron in the EAF. The presence of carbon represents an additional source of energy in the EAF because burning of carbon by injecting oxygen reduces the electricity consumption, consequently enabling a faster melting of the charged materials. Additionally, the carbon enables the formation of a foamy slag in the EAF. The preferred optimum carbon content in the DRI is about 1.5–3% depending heavily on the material input and the produced steel grades [14]. Natural gas and CO aid to maintain the desired carbon content, as describe by the following carburization reactions (Eq. 5-7) taking place in the DR-shaft.

$$3\ Fe + CO + H_2 \rightarrow Fe_3C + H_2O \quad (5)$$

$$3\ Fe + CH_4 \rightarrow Fe_3C + 2H_2 \quad (6)$$

$$3\ Fe + 2CO \rightarrow Fe_3C + CO_2 \quad (7)$$

The electric arc furnace is the most important scrap recycling process. Most of the EAF`s are operated based on 100 % scrap input. However, alternative products like DRI or HBI can be used as charging materials together with scrap. Hot DRI is applied for combined DR-EAF plants whereas HBI can be transported and thus also be used in stand-alone EAF plants. HBI melting in the EAF consumes more electric energy than scrap due to the presence of acid gangue in the iron ore which must then be neutralized by lime addition, increasing the volume of slag compared with conventional melting of scrap. On the other hand, higher temperatures of the DRI can also lead to lower energy demands in the EAF due to the contained sensible heat of the pre-heated DRI. A high percentage of metallization helps to keep energy consumption under control [15]. Thus, depending on the share of scrap and DRI (increasing DRI amounts lead to higher energy demands), temperature of DRI, specific slag mass, etc. the EAF energetic requirements will fluctuate between 310–640 kWh t/CS [16].

Table 4 shows typical mass- and energy balances results for a natural gas-based DR-process in combination with an EAF. In order to reach a reduction degree of the hot DRI product of 95 %, 1.4 tons of iron oxide input material containing input materials per ton of DRI are required. Based on natural gas which contains approx. 95 % methane, the simulation results in a NG-demand of approx. 255 m^3_{STP}/t DRI or 218 m^3_{STP}/t CS.

For the simulation of the direct reduction process, the proportion of used scrap was kept the same as the basic oxygen furnace, with the purpose of obtaining comparable products through both processes. Based on this assumption 857 kg of hot DRI are required for the production of one ton crude steel. Using hot DRI at a temperature level of about 500 °C as input material leads to an electricity demand in the EAF of 358 kWh/t CS. Compared to the values mentioned above, the electricity demand based on the simulation is rather low. The reason therefore is the high temperature of the hot DRI which provides sensible heat for melting the DRI.

Table 4: Results from the energy and mass balance calculations for the DR(CH_4)/EAF process

DR production					
input	pellets	1391.3	kg/t DRI	1191.6	kg/t CS
	lime	0.4	kg/t DRI	0.3	kg/t CS
	natural gas	255.0	m³STP/t DRI	218.4	m^3_{STP}/t CS
	electricity	112	kWh/t DRI	95.9	kWh/t CS
output	DRI			856.5	kg/t CS
EAF					
input	DRI			856.5	kg/t CS
	Scrap			270.5	kg/t CS
	coal			20.0	kg/t CS
	burnt lime			24.0	kg/t CS
	dolomite			17.9	kg/t CS
	refractory			0.1	kg/t CS
	natural gas			50.9	kWh/t CS
	oxygen			41.1	m^3_{STP}/t CS
	electricity[1)]			368.2	kWh/t CS
output	Steel			1000	kg/t CS
	Slag			132.1	kg/t CS
	EAF off gas			575.6	m^3_{STP}/t CS

[1)] Hot DRI input in EAF (~500 °C) ensuring utilisation of sensible heat

2.1.4 The hydrogen route

2.1.4.1 DR(CH_4)/EAF route & hydrogen addition

As the reforming gases of the natural gas-based DR-process already contain hydrogen, it can be used to partly replace natural gas in the direct reduction process thereby achieving a further reduction in CO_2-emissions. When using H_2 as reducing agent, a higher reduction degree from iron ore to iron is achieved [17]. However, the reduction process is thermally unfavourable, due to the endothermic nature of the reaction between hydrogen and iron oxide.

Following the information given by Ripke et al. [14] about 30 % of the natural gas can be replaced by hydrogen without any major process changes. This data, amongst others, was used in the DR(CH_4)/EAF model and resulted in a reduction of NG-demand by about 80 m^3_{STP}/t DRI and a corresponding hydrogen demand of 270 m^3_{STP}/t DRI (Figure 7). The model also compiled for higher $H_2/(H_2+CH_4)$ volume ratios up to 0.85. Figure 7 shows a reduction of the emitted CO_2 if larger amounts of natural gas are substituted by hydrogen. Nevertheless, for an increased addition of hydrogen, various factors which impact the operation of the DR-process have to be considered.

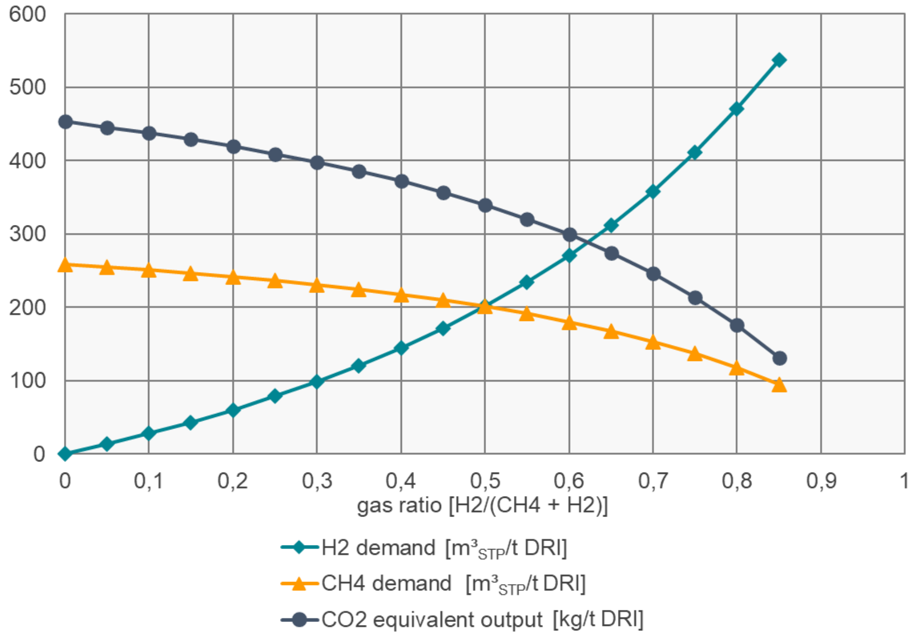

Figure 7. Reduction gas demand for DR(CH_4) process including hydrogen addition [18].

The replacement of natural gas by hydrogen leads to an increased volume flow in the shaft furnace (up to 30%) due to changes in gas compositions. Due to the increased gas amounts, different process conditions in the shaft furnace have to be considered. Different gas flows, residence times and operating conditions could affect the chemical reactions taking place in the furnace. Rising gas velocities will further lead to a higher pressure drop in the shaft furnace Moreover, gas compositions and temperatures as well as the metallization degree could be affected because of the change of reducing agents [18].

To summarize, the gradual implementation of hydrogen in the DR-process is the first step for a further reduction of CO_2-emissions.

2.1.4.2 DR(H_2)/EAF route

The hydrogen-based DR-process is operated almost without the utilization of carbonaceous fossil sources, the required energy input for the process has to be provided by alternative sources. In the case of hydrogen, it must be generated from renewable energy to obtain a CO_2-lean steel production. Thus, the electrolysis of water is currently the most promising technology for green hydrogen production.

As the addition of hydrogen to the natural gas-based DR-process without any changes in process configuration is limited, a direct reduction model with hydrogen (DR(H_2)/EAF), as seen in Figure 8, was developed for an input of about 95 % hydrogen. The remaining part is natural gas which is necessary to maintain process temperatures and the carbon content of the produced DRI. Process parameters and boundary conditions such as the amount and compositions of iron containing input materials, DRI temperature, composition etc. were kept constant compared to the DR(CH_4)/EAF model. In the hydrogen case, no reformer would be required. Instead, a gas heater will be attached to the system to preheat the gases to the required temperatures. Either hydrogen or other environmentally friendly heat sources (green electricity, waste heat etc.) might be used as fuel for the heater. At this point, it has to be considered that a sink for the top gas stream of the DR shaft must still be available to avoid an enrichment of nitrogen and other impurities in the system. For the current process configuration this is ensured by reusing part of the top gas as fuel input for the heater (see Figure 8) which is emitted via the stack.

Table 5 displays the results obtained from the simulations as well as the input parameters used. For producing 1 ton of crude steel around 638 m^3_{STP} of hydrogen are needed. Hydrogen is needed at two different process stages: in the shaft furnace for the reduction of iron oxides itself as well as sensible heat for heating up the reduction gas in the heater. In addition to this, 41 m^3_{STP}/t CS of natural gas are required as input to the system to maintain the desired carbon content in the DRI (see also section 2.1.3.2). The required amount of DRI as input in the EAF as well as the electricity demand of the EAF are in the same range as for the NG-based DR-EAF process.

Table 5: Results from the energy and mass balance calculations for the DR(H_2)/EAF process

DR production					
input	pellets	1391.5	kg/t DRI	1190.4	kg/t CS
	burnt lime	0.4	kg/t DRI	0.3	kg/t CS
	natural gas	48.0	m^3_{STP} /t DRI	41.1	m^3_{STP} /t CS
	hydrogen	745.5	m^3_{STP} /t DRI	637.8	m^3_{STP}/t CS
	electricity	112	kWh/t DRI	95.8	kWh/t CS
output	DRI			855.5	kg/t CS
EAF					
input	DRI			855.5	kg/t CS
	Scrap			270.2	kg/t CS
	coal			20.0	kg/t CS
	burnt lime			23.6	kg/t CS
	dolomite			17.6	kg/t CS
	refractory			0.1	kg/t CS
	natural gas			50.9	kWh/t CS
	oxygen			41.0	m^3_{STP}/t CS
	electricity[1)]			367.6	kWh/t CS
output	Steel			1000	kg/t CS
	Slag			130.0	kg/t CS
	EAF off gas			575.4	MJ/t CS

[1)] Hot DRI input in EAF (~500 °C)

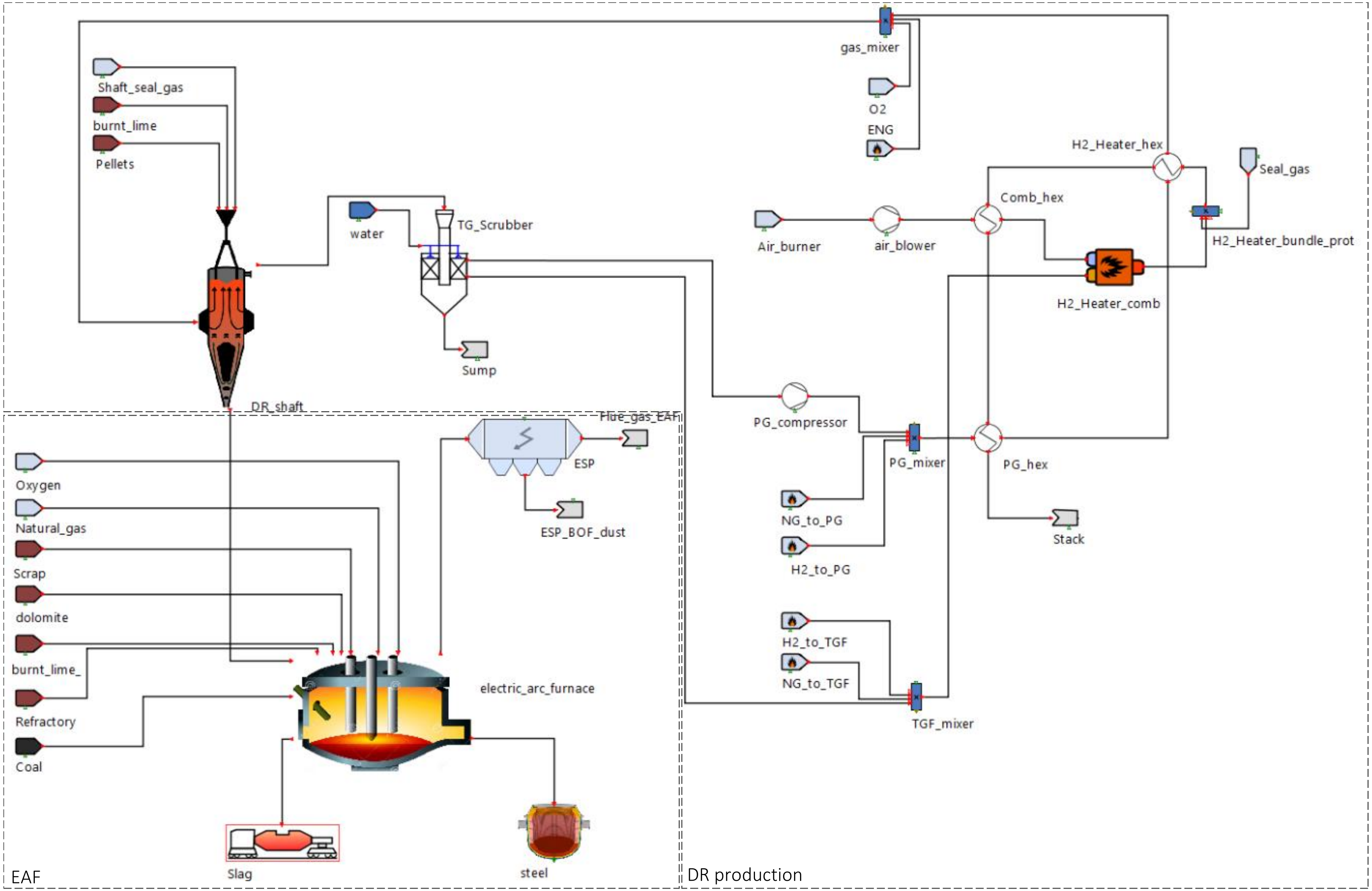

Figure 8: Process scheme and system boundaries of DR(H2)/EAF process

2.2 Environmental impact

2.2.1 CO_2-footprint conventional and low-carbon steel plant configuration

The iron and steel industry is one of the biggest industrial emitters of CO_2. It is estimated that between 4 and 7 % of the anthropogenic CO_2-emissions are produced from this industrial sector [10]. Current total CO_2-emissions of the most prevalent steelmaking process, the BF/BOF route, are reported in the range of 1,650-1,920 kg CO_2/t CS depending on process configurations, system boundaries etc. [19], [20], [21], [22]. The bandwidth of emission values of DR(CH_4)/EAF presented in literature is spread due to different processes which can be applied, varying scrap/DRI input ratios in the EAF and CO_2-intensities of the electricity used for running the EAF. In general, the emission level is significantly lower than for BF/BOF and is rated between 600-1,200 kg CO_2/t CS [19], [20], [21], [22], [23]. There is little information available regarding the CO_2-emissions of DR(H2)/EAF, varying between 50-340 kg CO_2/t CS [19], [22].

In order to determine which effective CO_2-reduction potential is achievable with the hydrogen route in comparison with the current production routes, the models described above in section 2.1.3.1, 2.1.3.2 and 2.1.4.2. were analysed in detail regarding their CO_2-emissions. As described in Figure 9, the CO_2 directly emitted from BF/BOF was calculated including the emissions corresponding to the coking and sintering processes, as they represent an important source of CO_2. Sinter is practically always produced at the steelworks onsite as it is prone to degradation during transport and handling. Neither pelletizing or lime production were simulated, as pelletizing is mainly carried out at the site of the mine and therefore does not usually belong to the integrated steelworks and lime is as well produced outdoors from the steel mill [24]. Nevertheless, the amount of their corresponding CO_2-emissions was taken from the literature and was considered as upstream emissions to have a complete overview of the entire CO_2-emissions coming from the different production routes and the influence of every single process in the total amount of CO_2 emitted. Further upstream emissions from various input streams (e.g. natural gas, iron ores etc.) were neglected. As a large share of by-product gases arising from the coking, BF- and BOF-process are used for the generation of electricity in the power plant, these emissions were also taken into account as direct emissions.

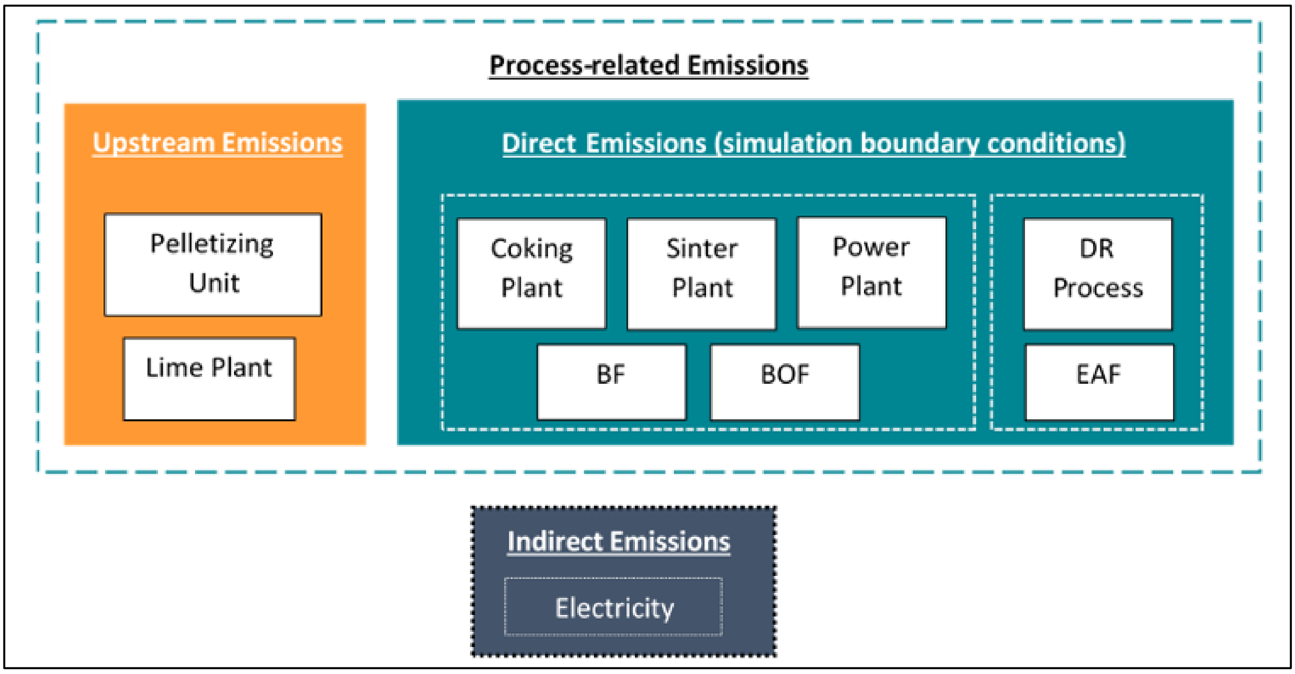

Figure 9: System boundaries for the calculation of the CO_2-emissions

Direct, upstream and indirect emissions were calculated for the three production routes. Figure 10 shows the process-related CO_2-emissions (direct and upstream) from the three studied production routes. As outlined, the production of crude steel through the DR/EAF represents a significant drop on the process-related CO_2-emissions from ~1,900 kg CO_2/t CS for the BF/BOF route to ~630 kg CO_2/t CS and 280 kg CO_2/t CS for the DR(CH_4)/EAF and DR(H_2)/EAF respectively. The majority of the process-related emissions originates from direct emissions for the BF/BOF and the NG-based DR-process whereas for the hydrogen-based process the direct and upstream emissions are in the same range. Generally, DR-processes leads to higher upstream emissions as the amount of externally purchased pellets is higher than for the BF/BOF route (see section 2.1.3 and 2.1.4). Referring to the process-related emissions, reduction rates of 67 % for the DR(CH_4)/EAF and 85 % for the DR(H_2)/EAF route can be achieved compared to the BF/BOF reference process.

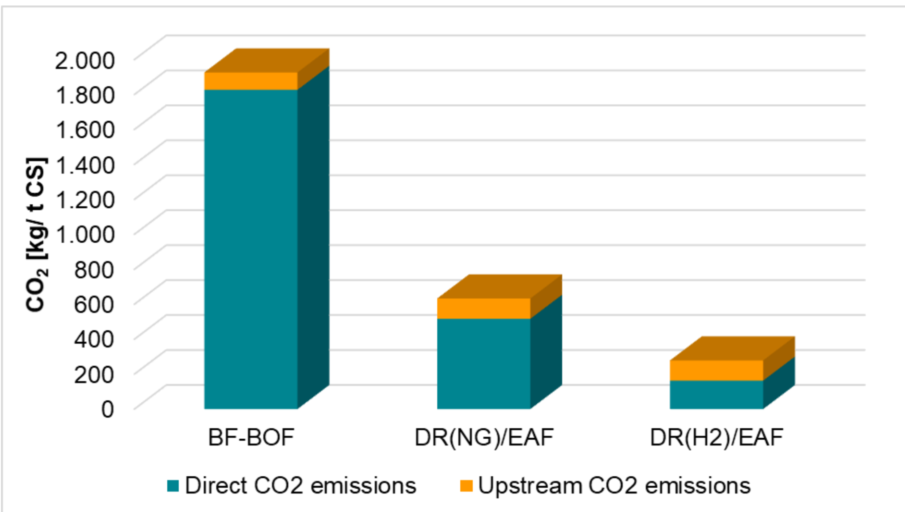

Figure 10: Process-related CO_2-emissions from BF/BOF, DR(CH_4)/EAF and DR(H_2)/EAF

One of the main factors affecting the overall amount of CO_2 emitted is the carbon intensity of the electricity produced, as seen in Figure 11. According to the European Environment Agency, 295.8 g of CO_2 per kWh generated electricity is the current average for the EU (data for 2016) [25]; although this value can substantially differ from one country to another. Whereas the effect of the indirect emissions on the total CO_2 emitted from the BF/BOF route is practically negligible and play a minor role for the natural gas-based route, they have a huge impact on the overall CO_2-emissions in the case of the hydrogen-based route. Taking the current CO_2-intensity into account, the production of crude steel via DR(CH_4)/EAF still produces 61 % less CO_2 than the BF/BOF process. In contrast to this, the production of crude steel via the hydrogen route produces approximately 25% more emissions than through the DR(CH_4)/EAF. Compared to BF/BOF a reduction of 34 % is achieved. However, the reduction achieved when using natural gas or hydrogen is far away from the 80% reduction target.

In order to illustrate the impact of different CO_2-intensities Figure 11 also depicts the overall CO_2-emissions for 100 % renewable based electricity as well as the upper range of the current CO_2-intenstities of the majority of the EU-countries which is at the moment at around 500 g/kWh [25]. As DR(H_2)/EAF is the most affected route by the variation of the carbon footprint linked to the generation of electricity, the overall CO_2 load is in the range of 280 to ~2000 kg CO_2/t CS. For the latter no emission reduction can be reached compared to BF/BOF. On the contrary, using 100 % CO_2-free electricity leads to an overall CO_2-reduction for the hydrogen-based route of 86 %. Further reductions are possible if the remaining natural gas in the DR-process is replaced by e.g. bio-based gas, emissions from the EAF are further reduced and/or upstream emissions from pelletizing are minimized by switching to CO_2-lean energy input sources.

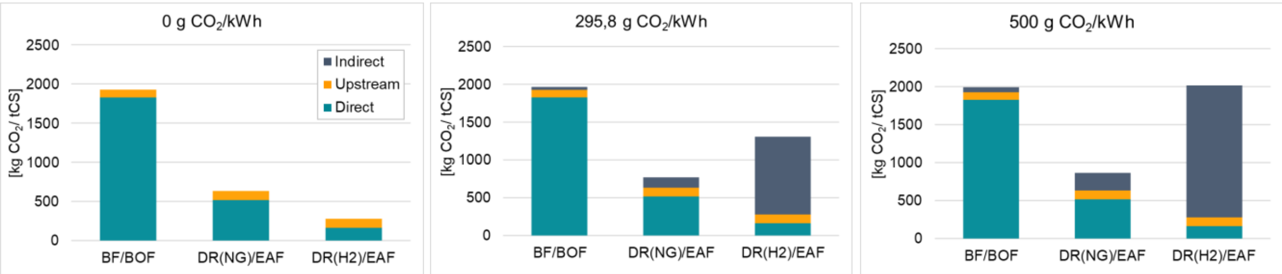

Figure 11: Influence of the indirect emissions on the total amount of CO_2 emitted

With proper conditions however, the direct reduction with hydrogen can lead to the avoidance of the bulk of the CO_2-emissions during the production of crude steel. This is only possible when the indirect emissions are prevented by using carbon-lean electricity. Thus, the goal of minus 80 % can be reached if the CO_2-intensity falls below 30 kg CO_2/t CS.

2.2.2 Energy demand conventional and low-carbon steel plant configuration

Steel production is energy intensive. The energy consumption of crude steel production can vary considerably depending on the production route itself as well as on other additional factors as the sort and quality of the iron ore and the coal used, the final steel product, etc. In addition, energy will be likewise utilized for related purposes as for instance, the transportation of raw materials. The table below (Table 6) shows the main energy inputs and their applications [26].

Table 6: Main energy inputs

Energy Input	Application as energy	Application as energy and reducing agent
Coal	BF, sinter and coking plant	Coke production, BF pulverised coal injection
Electricity	EAF, rolling mills and motors	
Natural gas	Furnaces, power generators	BF injection, DRI production

The main energetical driving force of the BF/BOF route is the chemical energy from the reactions between the input materials and the element carbon. The chemical energy required for the reduction of iron ores is provided by carbon-based reducing agents as coal or coke. Those carbonaceous agents also supply energy for the heat needed to reach the required temperatures. By-product gases as BF gas, BOF gas or coke oven gas (COG), are used again in various process steps in order to save additional fossil fuels and energy resources. Among other processes, those gases are being used for the blast furnace, the coking plant and the hot and cold rolling mill. Alternatively, those process gases can be used for power generation and district heating. They will be only flared in the absence of any use option. Figure 12 shows the surplus of electrical energy available when the process gases are entirely transformed into electricity, using gas and steam turbine generators with an overall electrical efficiency of around 37%.

Since direct reduction is an entirely different process, its energy balance differs from the blast furnace route. The auxiliaries and the presence of the EAF as a part of the process chain in the direct reduction processes will increase the electrical demand of the process itself when compared with the reference route. Approximately 80-125 kWh/t DRI are necessary to cover the electricity demand for auxiliaries such as compressors, water supply and others [27], [28]. Operating an EAF requires an additional amount in the range of 310-640 kWh/t CS depending on the share of scrap/DRI, temperature of DRI, specific slag mass etc. [16]. In contrast to the off gases of the BF/BOF route that can be used as fuel for heating and electricity production, the DR/EAF-waste gases have no further practical use due to their low calorific value as a consequence of the high N_2 and CO_2 content in these gases.

Additional electricity will be required for the direct reduction with hydrogen, as an electrolyzer will also be necessary. An additional electricity demand of approximately 3,000 kWh/t CS is estimated for the production of hydrogen, considering an electrolysis efficiency of 75 % based on the higher heating value of hydrogen (3.54 kWh/m^3_{STP}). This data includes the generation of the reducing gas as well as the hydrogen demand for heating the reducing gas. If the hydrogen demand for heating could be provided by waste heat from other processes or other alternative energy sources an increased efficiency can be reached. This will result in a remaining minimum energy demand of 1,900-2,100 kWh/t CS which is required for the reduction of iron ores itself.

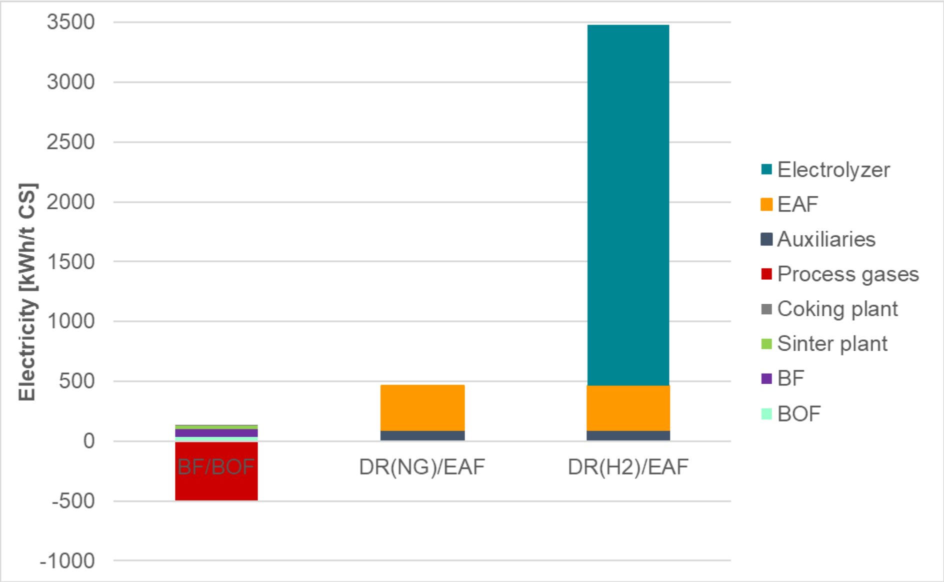

Figure 12: Electricity flows for the DR(CH_4)/EAF, DR(H2)/EAF and BF/BOF routes

2.2.3 Influence of scrap on environmental impact

The share of scrap and DRI added to the EAF has a remarkable influence on the hydrogen requirements, CO_2-emissions and EAF-energy demand. To study its influence, several calculations were carried out. For the calculations, the iron input carriers into the EAF were limited to DRI and scrap. The total iron content in the EAF was maintained constant whereas hot DRI (at a temperature level of about 500 °C) was stepwise exchanged by scrap. As depicted in the following graph (Figure 13), the hydrogen demand drops down with decreasing DRI input into the EAF. The higher the DR/HBI input in the EAF, the more DRI/HBI should be produced and therefore, the higher the hydrogen consumption will be. According to the simulations, the hydrogen requirements can vary from 0 to 830 m^3_{STP}/t CS depending on the amount of scrap charged to the EAF. The hydrogen requirements are the sum of the hydrogen needed for the reduction of the iron ores in the shaft oven and the hydrogen used as fuel in the gas heater (see Figure 8).

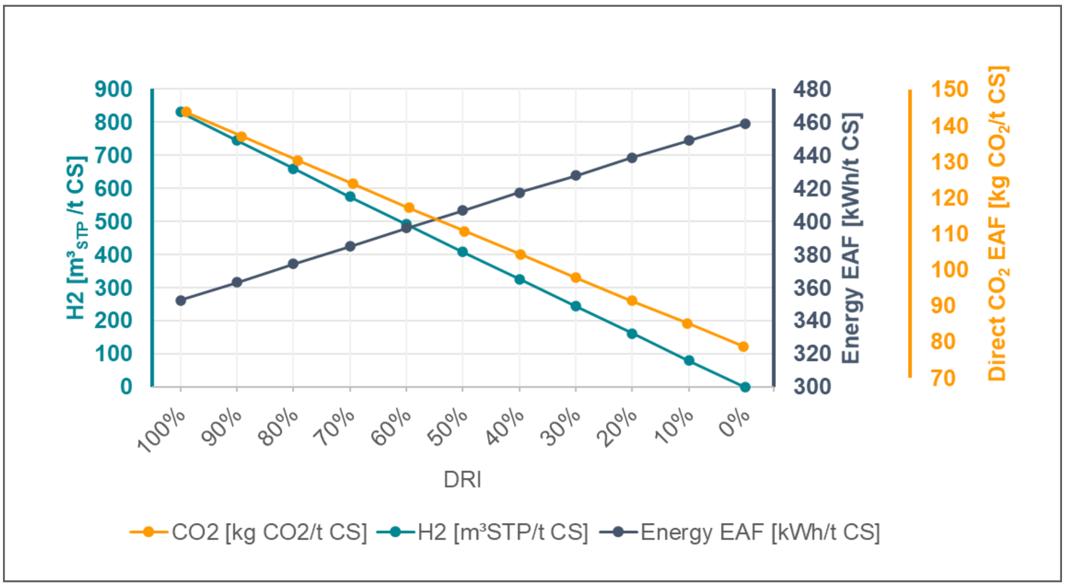

Figure 13: Influence of the Hot-DRI share on direct CO_2-emissions, energy demand in the EAF

Figure 13 shows the influence of the Hot-DRI/scrap shares on the electrical energy demand and direct, process related CO_2-emissions from the EAF. Assuming the hot DRI-input into the EAF (around 500 °C), higher energy requirements with decreasing amounts of Hot-DRI in the EAF are revealed. Approximately 100 kWh per ton of crude steel produced could be saved at the EAF when using exclusively DRI(H_2). The reduced electricity consumption at higher amounts of DRI in the EAF is the result of two effects: (I) The considerably higher DRI-temperature in comparison to the inlet temperature of scrap (which enters the system at room temperature) is responsible for a reduction in the EAF-energy consumption. (II) The energy released as a result of the reaction between the carbon present in the DRI and the oxygen injected, reduces the electricity consumption in the EAF and thus allows a faster melting.

As presented in Figure 13, lower shares of DRI input lead to a reduction of direct CO_2-emissions of the EAF itself. The reason therefore is the higher carbon content in the DRI compared to scrap. This carbon reacts with the oxygen injected in the EAF, simultaneously releasing CO_2 and energy, due to the exothermic nature of the reaction. The decrease of the CO_2-emissions with an EAF fully operated with scrap compared to an EAF functioning solely with DRI is approximately 65 kg CO_2 per tonne of crude steel produced.

To sum up, higher shares of scrap lead to reduced hydrogen demands for the production of DRI and subsequently lower electricity demands for the production of hydrogen. Additionally, lower direct emissions of the EAF have a positive impact on the overall CO_2-footprint of the steelmaking process. On the contrary, rising scrap input requires higher electricity demands for the EAF itself and therefore negatively affects the indirect CO_2-emission level of the EAF.

An additional topic of this study was the identification of the amount of scrap available for use in the DR(H_2)/EAF route in order to meet the forecasted demand of crude steel. The amount and quality of scrap has a large impact on the quality of the final steel and the amount of scrap which can be charged is dependent on the final grade of the crude steel to be produced via EAF. The considered total amount of scrap available was the sum of the following species: home scrap + prompt scrap +

obsolete scrap. The home and prompt scrap are generated in the production process (waste and errors) or in the production of steel-based products whereas the obsolete scrap refers to the scrap available from the end of life products and applications and depends on its recycling rate.

The impurities present in obsolete scrap affect the quality of final steel grades. For some final products where high-quality steel is needed, either high quality scrap or virgin ores must be used, whereas for other sectors the quality of scrap is not a limiting factor. Therefore, a deeper insight into the scrap grades availability and its corresponding crude steel quality must be carried out. However, this topic is out of the scope of the present study.

The future projected crude steel production (Figure 14) comprises the production of crude steel from virgin ores, through the BF/BOF or DR(CH_4)/EAF route or other minority processes, as explained before in section 2.1, as well as the steel produced via the scrap-based EAF route. In order to evaluate the future demand of hydrogen for the transition of the BF/BOF based towards hydrogen-based steel production routes, an unaltered share of scrap-based steel production is assumed. Taking the forecasts of home-, prompt- and obsolete scrap as the total scrap available in Europe until 2050 into account [5] (orange coloured column from Figure 15) and considering that a share of this scrap (grey column) will be still utilized via EAF`s running on 100% scrap, the scrap available for the direct reduction route with hydrogen will be in the range between 27 and 33 Mt scrap/ year from 2020 to 2050 (turquoise colour).

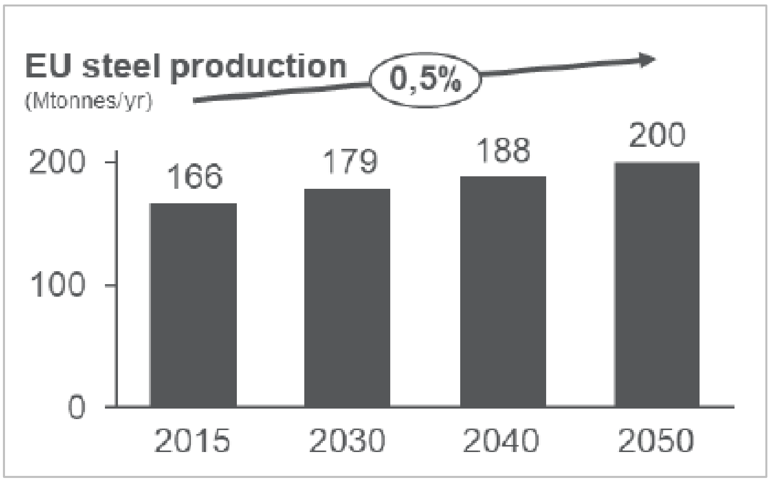

Figure 14: Steel production forecasts until 2050 [5]

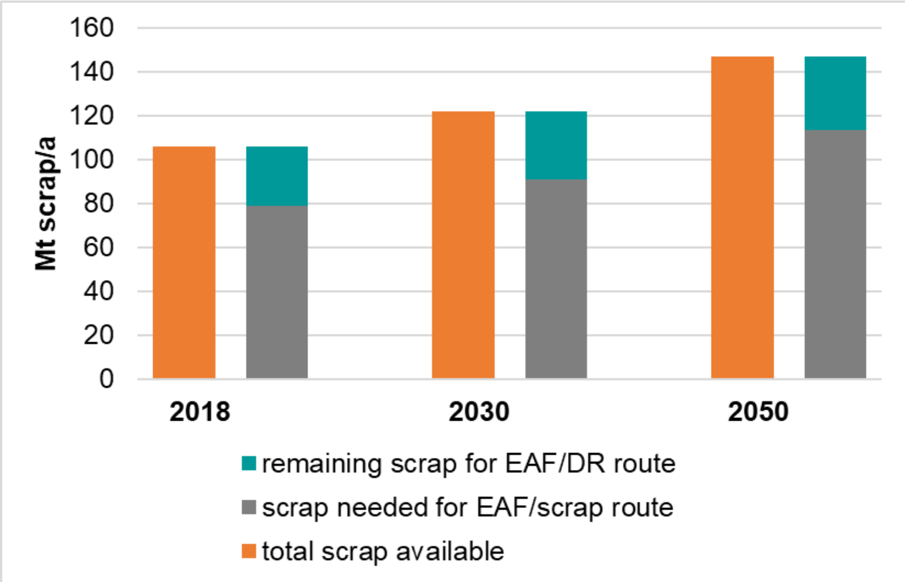

Figure 15: Forecasted scrap availability [5]

As explained in Figure 13 the hydrogen demand for the DR(H_2) route strongly depends on the DRI/scrap share charged into the EAF. In order to calculate the hydrogen requirements for the European steel industry until 2050, it was considered that the entire steel produced from virgin ores (excluding the production via the scrap route) will be produced via the DR(H_2)/EAF route, assuming the complete decarbonization of the steel industry. For these calculations, the scrap available for the direct reduction route with hydrogen presented in the graph above (Figure 15) as well as the forecasted crude steel production was considered.

To fulfil the demand gap between the forecasted total crude steel production and the production of crude steel via the scrap route, the DRI produced via the DR(H_2)/EAF route should be between 75 and 82 million tonnes per year. Taking into account that approximately 745 m^3 of hydrogen are needed per tonne of DRI produced, this corresponds to a yearly hydrogen production in Europe between 56 and 61 billion cubic meters of hydrogen per year or 5 to 5.4 million tonnes respectively (see Figure 16).

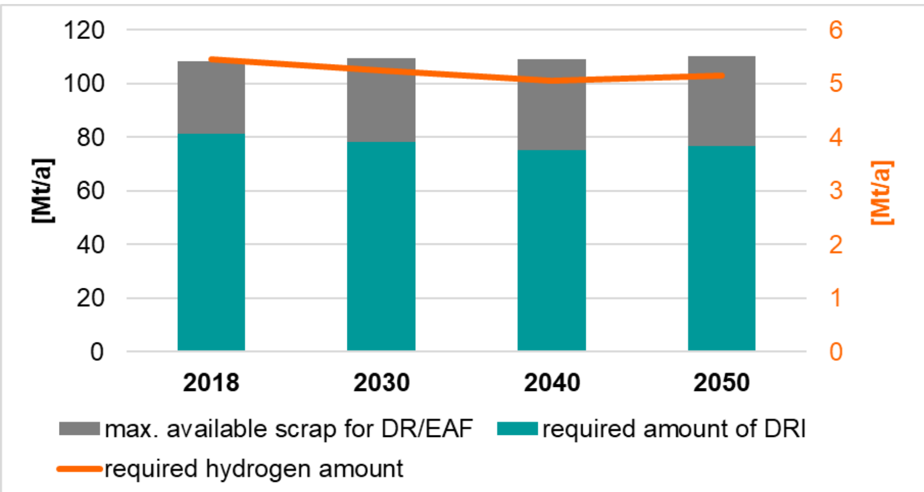

Figure 16: Hydrogen demand to meet the forecasted crude steel production via DR(H_2)/EAF

2.3 Exploitation of results for the steel industry in EU28

In order to get an impression of how the transition of the European Steel Industry towards carbon-lean processes can look like and how this transition will influence the energy system, the previously presented results are rolled out on a European level. As the transfer of the BF/BOF route has the highest environmental impact, the calculations are based on the current amounts of steel produced via the BF/BOF route given in section 2.1.1. The goal is to analyze the future demand of hydrogen and subsequently electricity if the steel industry is completely transferred to carbon-lean processes like the DR(H_2)/EAF process.

Figure 17 depicts the hydrogen as well as the remaining natural gas demand for the individual European steel producing countries assuming the amounts of reducing gases derived from the process simulations (638 m^3 H_2/t CS, 41 m^3 CH_4/t CS). The presented numbers (see Annex) indicate a maximum scenario as a transfer of the whole amount of crude steel produced by BF/BOF to the hydrogen-based route is assumed. This will lead to an overall hydrogen demand for the EU28 of 62.5 billion m^3/a or 5.6 million t/a, respectively. Furthermore 4 billion m^3 of natural gas will be needed for maintaining the carbon content in the produced DRI. The highest amounts of hydrogen will be needed in Germany with around 19 billion m^3/a followed by France, Netherlands (4.3 bn m^3/a) and Austria (3.9 bn m^3/a) representing the countries with the highest amounts of steel produced by the BF/BOF process. Following the increase of overall steel production (see Figure 14) higher demands of hydrogen have to be considered for future projections.

As previously described, there are some options to lower the required amounts of hydrogen: Increasing the share of scrap in the EAF leads to a reduction of DRI needed and subsequently to a lower demand of hydrogen per ton of crude steel (see also Figure 13). However, the amount of scrap cannot be increased arbitrarily as there is a significant influence on the required steel quality. The amount of hydrogen could also be reduced by using alternative energy sources for heating the hydrogen stream in the DR-process.

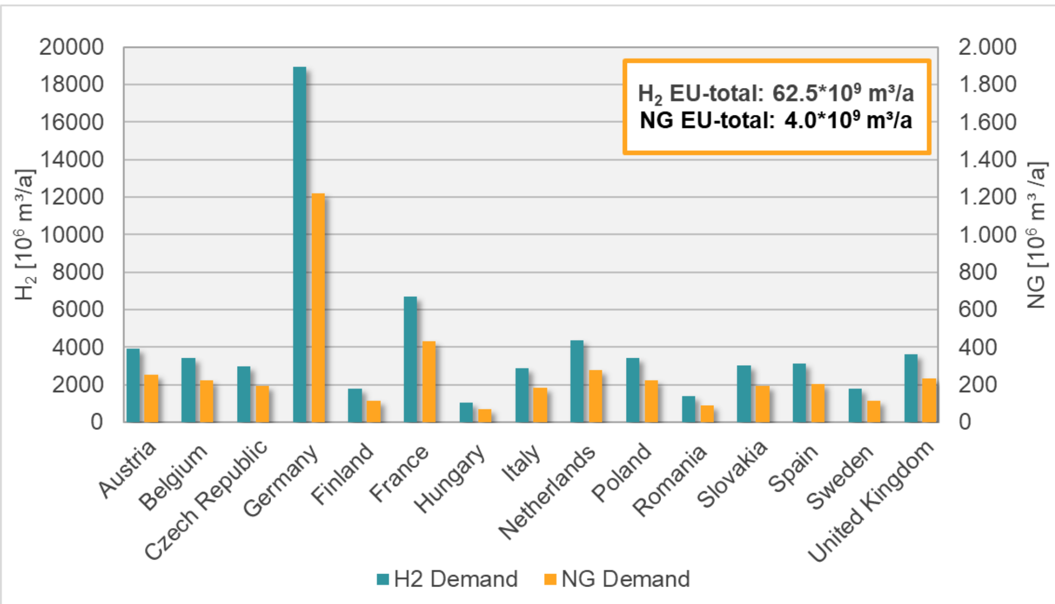

Figure 17: Hydrogen and natural gas demand for European steel production

As the utilization of hydrogen will lead to an enormous increase in the European electricity demand, the required needs are also analyzed for the different countries (see Figure 18; Annex). The presented data refer to the additional electrical energy demand which is needed for the transition to hydrogen-based steel production and have to be counted on top to the current electricity demand of the steel industry. In total, additionally 340 TWh will be required for EU 28. An important increase, considering that the actual electricity consumption of the steel industry is on the order of 75 TWh and that the additional electricity requirements correspond to 18 % of the current EU total consumption [10]. The electricity needed for the production of hydrogen is calculated to be ~300 TWh/a, the remaining part accounts for the electricity needed for the EAF- and DR-process itself. The amounts of electricity needed for the different countries correspond directly to the hydrogen demands. Therefore, the largest electricity demand will be needed in Germany (103 TWh/a), in Austria around 22 TWh/a will additionally be needed for producing hydrogen-based steel.

Even if the additional energy demand would be lower due to the application of other low-carbon or scrap-based steelmaking routes for example, the development of suitable electrolyzers as well as the supply of sufficient amounts of renewable energy will be a huge challenge for all involved stakeholders, which must be tackled in future.

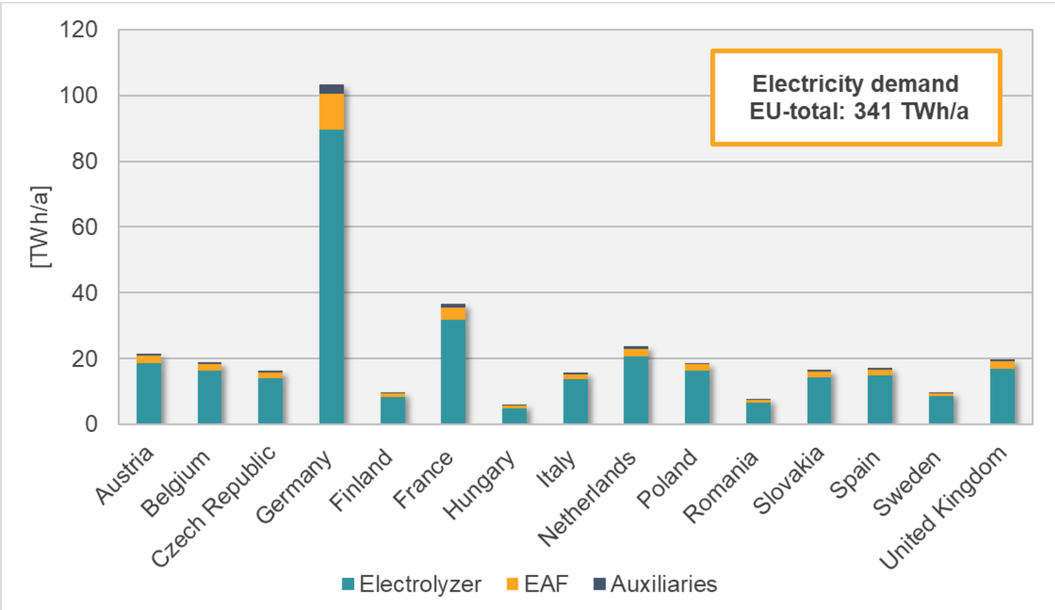

Figure 18: Additional electricity demand for European steel production

3 Allowable costs of hydrogen

3.1 Costs of steel production

To have a deeper insight on the overall costs, the production costs of steel trough the three different routes ((I) BF/BOF, (II) DR(CH_4)/EAF and (III) DR(H_2)/EAF) are analysed in the following section. After determining the price of the crude steel under the current technical and economic conditions, estimated production costs for the previously described scenarios are calculated. As presented below, variables such as the electricity price, the CO_2- and NG-price, the investment costs of the electrolyzer, etc. significantly influence the production cost of crude steel. Once the current and potential cost of the three production routes were determined, it was possible to determine in which point of time and under which particular technical and economic conditions the production of steel through the hydrogen route becomes an economically viable solution for the steel industry.

3.1.1 Reference case – baseline

The reference case encompasses the crude steel production costs correlated to the three production routes: BF/BOF, DR(CH_4)/EAF and DR(H_2)/EAF under the current conditions. For this evaluation, an overall calculation tool was created. This calculation relied on individual calculations as well as on the following literature sources: [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39].

To provide a better overview of the evolution and interdependency of the costs, these were divided into costs independent from any economic or political scenario (defined as “constant costs”) and costs which are highly influenced by external factors and future scenarios (defined as “changeable costs”). Constant costs include costs for raw materials, service, labor and capital (wear and tear) [36]. The list of the raw materials included in the constant costs (in the sense of keeping them constant in this cost analysis) is described in the material balance table below (Table 7).

Table 7: Raw materials included in the constant costs

Raw materials and processes			
BF/BOF	**Coking plant**	DR(H_2-CH_4)/EAF	**Shaft oven**
	Coking coal		Pellets**
			Burnt lime
	Sinter Plant		
	Iron ore (fines+ others)		**EAF**
	Coke breeze		Scrap
	Limestone		Coal
			Burnt lime
	BF		Alloys
	Lump ore		Dolomite
	Pellets		Oxygen
	Limestone		
	Coke		

	PCI coal		
	Oxygen		
	BOF		
	Scrap		
	Lime		
	Dolomite		
	Alloys		
	Oxygen		

It must be noted that the pellets used for the direct reduction process requires higher quality levels than the pellets used in the BF process and therefore their market price is 15-20 % higher. In the BF process it is possible to use lower-grade iron input materials because the impurities are removed through the formation of liquid slag. However, in the DR-process this liquid phase is not produced in the shaft, which consequently affect the impurities which are concentrated rather than removed. Therefore, only high purity low gangue, iron ore pellets can be used.

It should further be mentioned that the capital costs for the steel production processes (BF/BOF and DR/EAF) includes expenditures for retrofitting and maintenance of already existing plants but no depreciation allowances for the investment in new plants. The reasons for this approach are: (i) investment costs for new BF/BOF and DR/EAF are in the same order of magnitude (BF/BOF: 442 €/t CS, DR/EAF: 414 €/t CS) [20], (ii) BF/BOF will possibly only be replaced by DR/EAF plants if they have reached their end of the lifetime, (iii) the replacement of existing plants won`t take place at the same time but there will be a stepwise exchange of old aggregates depending heavily on specific environmental and local conditions of the plants. These reasons make a realistic implementation of investment costs at the current stage practically not viable. Furthermore, for a comparison of the different routes the cost proportions would stay in the same range. Thus, the validity of the results still exists.

The second part of costs considered in this analysis are changeable costs which consist of electricity, natural gas, CO_2-prices as well as operational costs for the electrolyzer (e.g. maintenance, labour etc.). The costs for the electrolyzer are assumed to change significantly within the regarded period so that they are included in the changeable cost. As this process step is an additional plant and must be implemented in all regarded cases, the depreciation expenditures of the investment as well as operation costs (in addition to the electricity) are included in the following results.

Figure 19 represents the costs per ton of crude steel produced in Europe via the BF/BOF route, the DR(CH_4)/EAF and the DR(H_2)/EAF pathway, under the current economic scenario. The calculated production costs are 490, 487 and 669 €/t CS respectively.

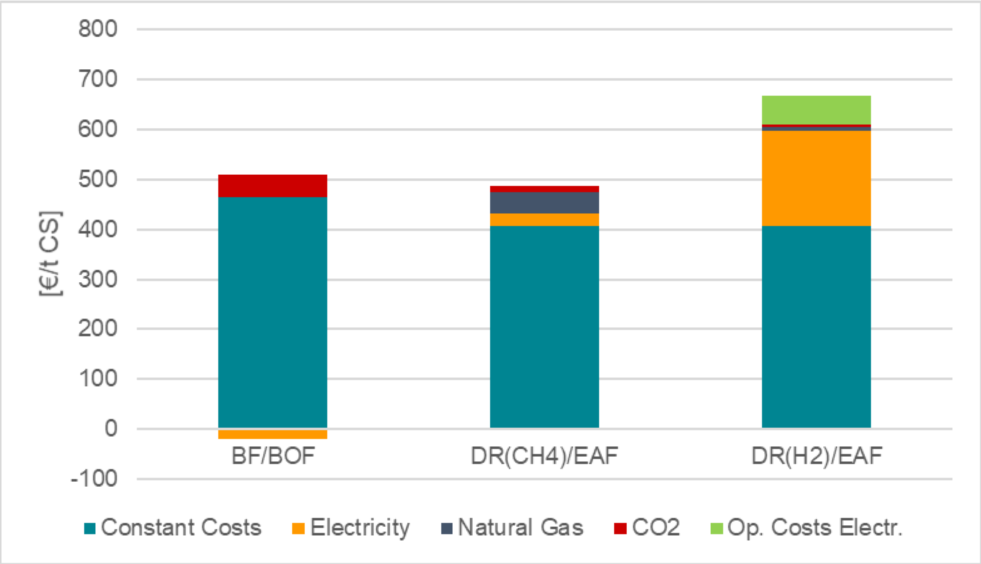

Figure 19: Overview of the crude steel production costs (reference case)

It is necessary to emphasize that the electricity, natural gas and CO_2-expenditures are European average values (see Table 8) for today. Therefore, the presented figures might differ for every country depending on its individual fares. Additionally, it must be remarked that the CO_2-costs solely encompass direct process emissions within the system boundaries displayed in the process schemes. Any CO_2-costs linked to upstream emissions and indirect emissions are included in the associated prices in these calculations. In addition, any free allowances accounting to the EU-ETS are not taken into account, as the goal is the comparison of the relevant routes.

Table 8: Parameters used for the calculations

Data Reference Case			
Compound	**Value**	**Units**	**Lit. Reference**
NG[1)]	18.5	€/MWh	[32]
Electricity[2)]	54.6	€/MWh	[33]
CO_2	24.6	€/t CO_2	[34]
Electrolyzer			
OPEX	30	€/kW	[38]
CAPEX	825	€/kW	[38]
Operating Hours	8000	h/a	
Depreciation	10	years	[38]
WACC	8	%	[38]

[1)] Prices excluding taxes and levies for non-household consumers, which consumption is greater than 4,000,000 GJ

[2)] Prices excluding taxes and levies for non-household consumers, which consumption is greater than 150,000 MWh

Focusing the attention on the allocation of the costs for every production route represented in Figure 19, it can be noticed that for the BF/BOF pathway, the constant costs represent almost 95% of the total costs. Approximately two thirds of the constant costs can be related to the raw materials and reducing agents whereas the remaining part includes the costs for labor, services and wear & tear. Regarding the total production costs, 10% come from the direct CO_2-emissions and approximately 5 % are net credits for the production of electricity out of the remaining process gases. As already discussed within the BF/BOF process chain valuable gases are produced. As explained in section 2.1.3.1, those gases are generally reused in the steel mill again for other purposes. Nevertheless, the balance borders represented here do not consider those processes. It is assumed, that excess gases are utilized for generation of electricity leading to a small cost credit.

The constant costs for the direct reduction process with natural gas entail approximately 80% of the total costs, whereas the natural gas, electricity and CO_2-emission costs represent 10%, 7% and 3% respectively. The split of constant costs is similar to the BF/BOF process (two thirds for raw materials, one third for the remaining part).

However, the costs breakdown for the hydrogen route is different. Whereas the constant costs are the same for both routes (direct reduction with natural gas and direct reduction with hydrogen), the costs linked to the electricity consumption are seven times higher for the hydrogen route. However, the natural gas and CO_2-costs present a reduction by a factor of 5 and 3 respectively, when comparing the DR(CH_4)/EAF and the DR(H_2)/EAF pathways. When comparing the costs of the DR(H_2)/EAF route with the BF/BOF and the DR(CH_4)/EAF routes, the constant costs, electricity, natural gas, CO_2 and the operational costs for the electrolyzer represent 60%, 28%, 1%, 1% and 10% respectively.

3.1.2 Sensitivity analysis

The sensitivity analysis will display the most important influencing factors on steel production costs for the various production routes. It must be remarked that the previously presented production costs of the BF/BOF route serves as the 100% base case for this analysis.

The future development of how low-carbon steel production processes will be integrated into existing processes are not yet completely clear and there are many possible variations of how exactly these transformation scenarios can unfold. Therefore, it is important to get an idea of how the cost structure will change with varying cost parameters such as electricity, CO_2, natural gas prices and costs for the electrolyzer. Furthermore, the influence of varying scrap inputs to the EAF on the overall steel production costs is also evaluated.

Based on this analysis, the allowable costs of electricity/hydrogen to produce low-carbon direct reduced iron, using H_2 as reducing agent are calculated. This factor will be of fundamental importance for the development of the rollout scenarios.

Figure 20 - Figure 22 show the results of the sensitivities of BF/BOF, DR(CH_4)/EAF and DR(H_2)/EAF production routes on the overall production costs. As the cost structure of the production routes differs from each other, there are different cost drivers. In general, the influence of the investigated parameters on the costs of BF/BOF and DR(CH_4)/EAF is lower than for DR(H_2)/EAF. Doubling the CO_2-price leads to an increase of ~10% for the costs of steel production via the BF/BOF route, whereas the dependency on CO_2-costs is much lower or neglectable for the DR-based routes. A higher electricity price for the BF/BOF route leads to lower production costs due to the net credits from the utilization of the excess process gases for electricity production. The main cost-driving factor for the DR(CH_4)/EAF route are the costs for natural gas. A cost increase of 100 % for natural gas leads to an increase of 10 % in the overall steel production costs. For the DR(H_2)/EAF route the

costs of electricity results in an increase of up to 30 % of production costs if the electricity costs double. Furthermore, the influence of costs for running the electrolyzer (CAPEX and OPEX) was also evaluated. A variation of +/- 100 % of the overall costs for running the electrolyzer which was rated on ~60 €/t CS for the reference case depending on operating hours, operation and maintenance costs as well as depreciation time and discount rates for the investment costs was assumed. This variation leads to an in-/decrease of the overall steel production costs of up to 10 %.

To summarize, low electricity prices and/or smart operation modes of the electrolyzer (as far as possible, considering the fact that a reduced operating time leads to an increase of installed capacities and the need for storage) as well as an overall decrease of electrolyzer costs is essential to realize an economic viable steel production based on hydrogen.

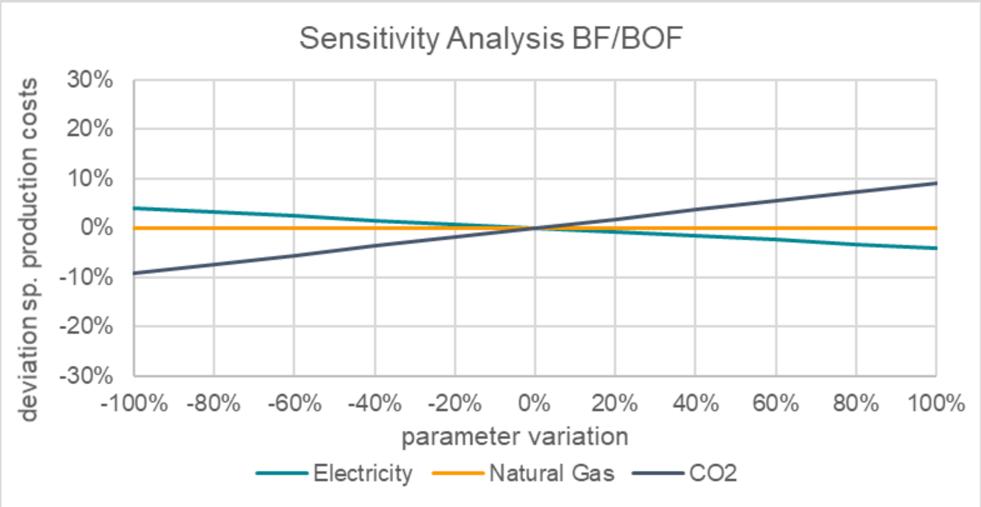

Figure 20: Sensitivity Analysis of BF/BOF steel production costs

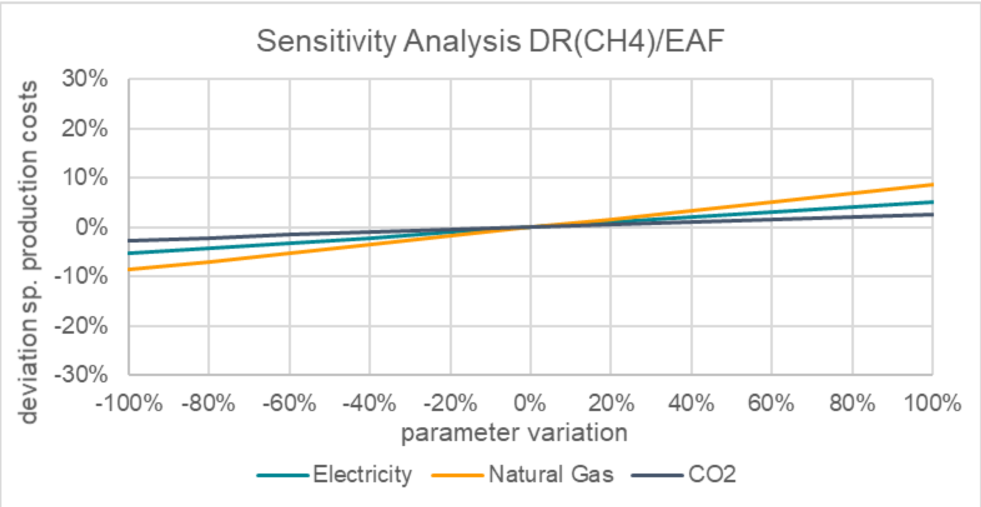

Figure 21: Sensitivity Analysis of DR(CH4)/EAF steel production costs

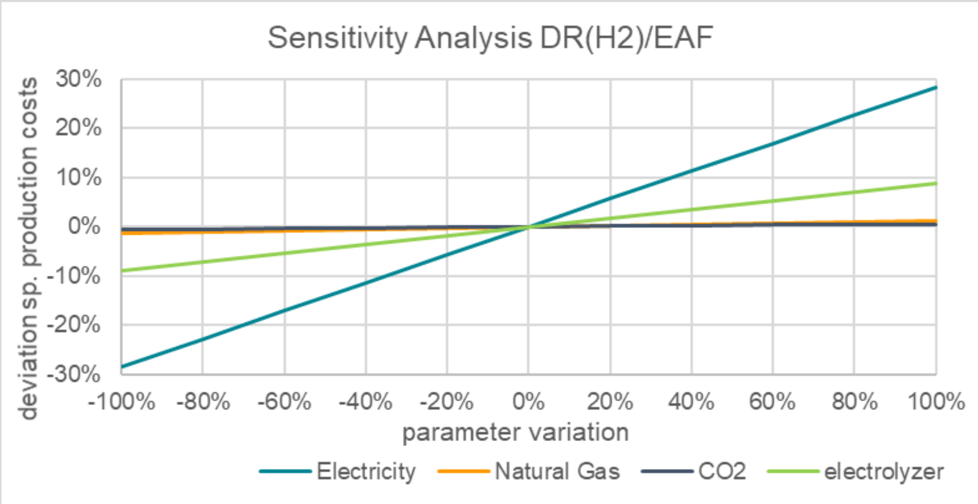

Figure 22: Sensitivity Analysis of DR(CH4)/EAF steel production costs

As already described in section 2.2.3, there is a significant influence on the energy and hydrogen demand as well as on the CO_2 of the EAF linked to the scrap vs. DRI balance. Subsequently, the influence of varying scrap inputs on the overall production costs is also analyzed and presented in Figure 23. The depicted values refer to the reference costs of the BF/BOF process (=100 %). The production costs of steel by the DR(CH_4)/EAF route only decrease slightly by an increased amount of scrap. Although there is a rise of raw material costs for higher shares of scrap, the lower costs for natural gas and CO_2 compensate this effect and lead to the overall minor decrease of costs. For the DR(H_2)/EAF route the costs significantly declines for higher shares of scrap. Rising the amount of scrap by 20 % leads to a reduction in the total production costs of 10 %. The reason therefore are the lower costs for the generation of hydrogen (electricity and costs of electrolyzer) as these are the main cost-driving factors for the DR(H_2)/EAF process. This issue has to be considered for a future roll-out of hydrogen-based steel production chains.

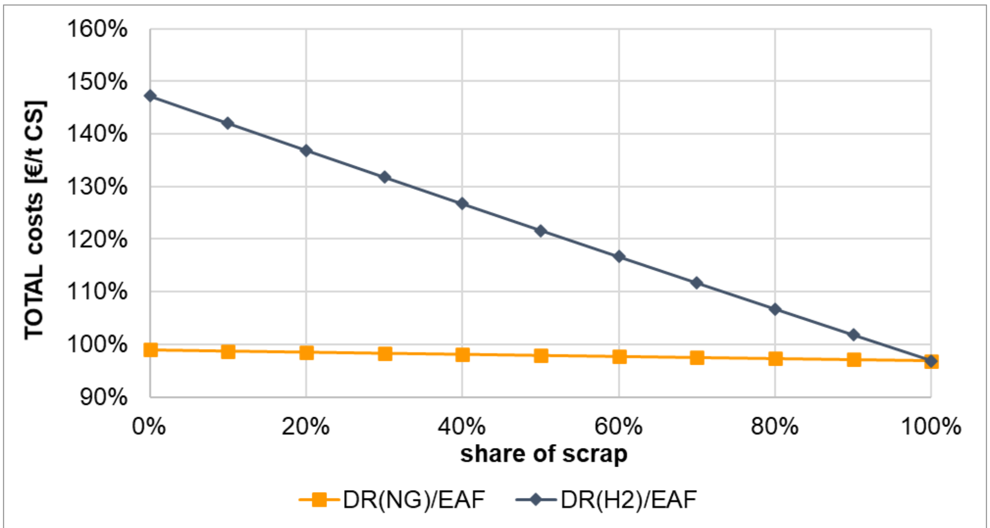

Figure 23: Dependency of production costs on scrap inputs (reference: BF/BOF)

3.1.1 Future outlook

In order to develop roll-out scenarios for the evaluation under which conditions hydrogen-based steelmaking could be a viable option for the European steel industry, different scenarios regarding the future costs of steel production are established. Therefore, outlooks on the cost development of natural gas and CO_2 are assumed according to the “Sustainable Development Scenario” specified in [35] whereas a range of varying electricity prices are taken into account. A decrease in CAPEX and OPEX for the electrolyzer was implemented in the calculations based on an outlook given by TNO and Siemens [37] (see Table 9). The remaining costs (e.g. raw materials including coking coal for BF/BOF, fixed operation costs,…) were assumed to be constant.

Table 9: Parameters used for future outlooks

Data Future Outlook				
Compound	**Units**	**2030**	**2050**	**Lit. Reference**
NG	€/MWh	21.7	22.5	[35]
CO_2	€/t CO_2	74.5	160.7	[35]
Electricity	€/MWh	0-100	0-100	
Electrolyzer				
CAPEX	€/kW	715	555	[37]
OPEX	€/kW	27	21	[37]

Based on these assumptions, the overall production costs for 2030 and 2050 were calculated depending on varying electricity prices and set in relation to the reference of BF/BOF steel production costs (see Figure 24 - Figure 25). Analyzing these developments, the significant influence of electricity prices on the DR(H_2)/EAF production costs appears. The reason therefore are the large amounts of electricity needed for the production of hydrogen. Regarding the DR(CH_4)/EAF there is also a slight increase of the overall production costs by rising electricity prices due to the considerable electricity consumption of the EAF. Furthermore, the costs of BF/BOF decline by increased electricity costs due to negative electricity prices caused by a surplus of process gases which can be converted into electricity.

Comparing the future projections on the development of productions costs for steel, it appears that there is hardly any difference between 2030 and 2050 for DR(H_2)/EAF. Declining costs for the electrolyzer (-23 %) are compensated by slightly higher costs for natural gas (+3 %) and CO_2 (+115 %). On the contrary, costs for DR(CH_4)/EAF and BF/BOF significantly increase from 2030 to 2050 but also compared to the reference case. Costs of DR(CH_4)/EAF projected for 2050 are about 9 % higher than 2030 due to the much higher CO_2-price and a rising natural gas price. The increase in costs of the BF/BOF route is even larger (+ 32 % between 2030 and 2050) which is mainly caused by the rising CO_2-prices and the higher carbon intensity of this route.

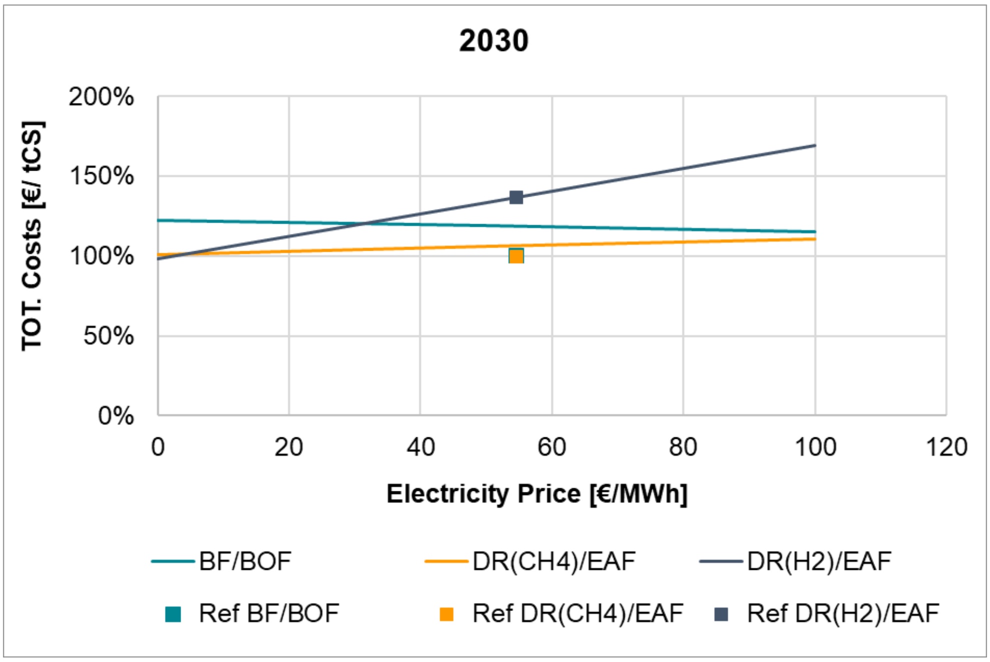

Figure 24: Outlook on steel production costs for 2030

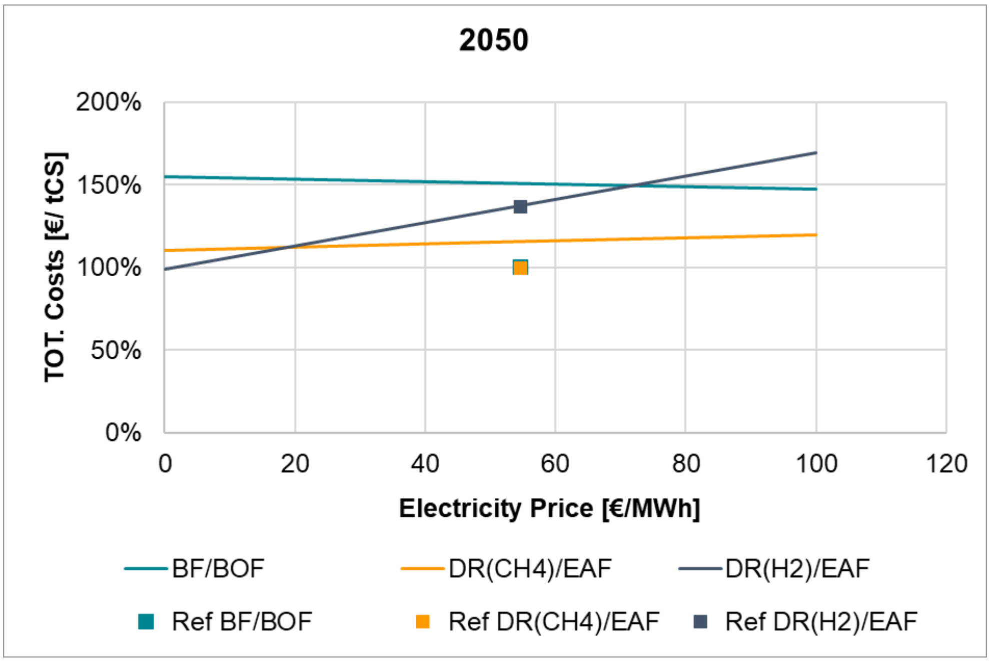

Figure 25: Outlook on steel production costs for 2050

In order to get a clear picture of the allowable costs of electricity for an economic viable hydrogen-based steel production, the previous presented results are summarized in Figure 26. The aim is to analyze the break-even ranges between the different steel production routes. Therefore, the ranges of production costs within the evaluated parameters are depicted depending on the costs of electricity.

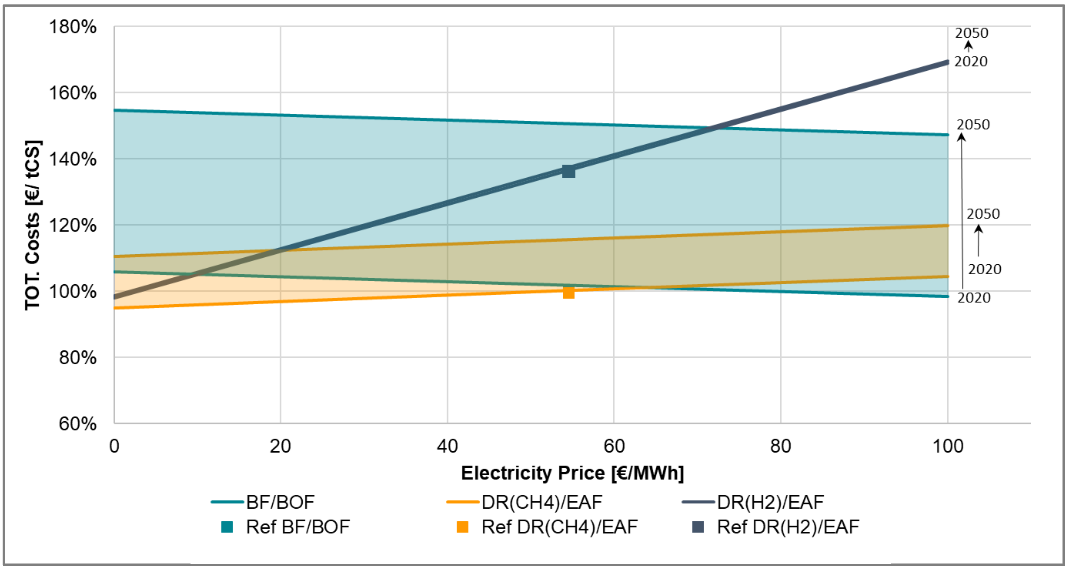

Figure 26: Break-even ranges of steel production costs and future projections

As the first step of the transition to a low-carbon steel production chain is assumed to be the transfer from the BF/BOF to the DR(CH_4)/EAF route it is important to analyze under which conditions the natural gas based route will be economically more viable than the reference process. Regarding the reference case, the production costs of BF/BOF and DR(CH_4)/EAF are on the same level whereas the break-even ranges vary from negative electricity prices to >>100 €/MWh mainly depending on the high influence of CO_2-costs on the BF/BOF production costs. Comparing the BF/BOF with the DR(H_2)/EAF route, there is a quite broad range of break-even costs. Assuming the cost situation in 2050, the hydrogen-based steel production becomes economically interesting below an electricity price of around 74 €/MWh whereas at the current situation the prices have to fall below 10 €/MWh. At this point, it also has to be mentioned that no investment costs for the installation of new plants are included in the calculation.

Following the second step of the decarbonization scenario, the transition from natural gas to hydrogen, the maximum allowable costs of electricity are around 20 €/MWh for an economically favorable utilization of hydrogen in 2050. This implies that the conditions for a hydrogen-based process will be difficult to meet. Positive aspects for favoring hydrogen instead of natural gas could be an even higher CO_2 and natural gas price, and a further decrease in the investment cost and the operation and maintenance cost of electrolyzers.

As the price of CO_2 is one of the main steering mechanisms for the implementation of low-carbon based technologies in future, Figure 27 depicts the break-even ranges of steel productions costs for the different route as a function of the CO_2-price (0-300 €/t CO_2) and varying electricity prices (0-100 €/MWh). Following the higher range of electricity price of 100 €/kWh the CO_2-price has to reach a level of ~235 €/t CO_2 to make hydrogen-based steelmaking economical more viable than BF/BOF. Compared to DR(CH_4)/EAF the CO_2-prices have to rise to levels >> 300 €/t CO_2. Taking the lower bandwidth of electricity prices of 0 €/kWh into account, the break-even of DR(H_2)/EAF related to BF/BOF is reached at ~10 €/t CO_2, referred to DR(CH_4)/EAF it is ~75 €/t CO_2.

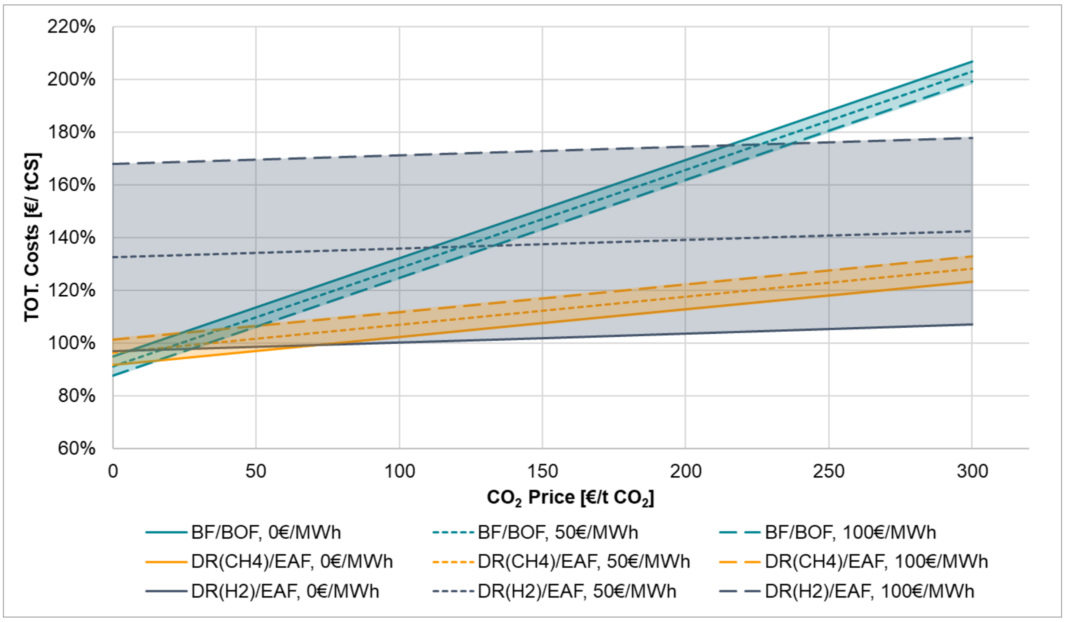

Figure 27: Break-even ranges of steel production costs as function of CO_2-price

4 Conclusions

The transfer of current steel production processes towards breakthrough-technologies is essential to reach the goals of the European steel industry aiming at a CO_2-reduction of 80-95 % by 2050. As hydrogen-based steelmaking is seen as one of the most promising options to realize CO_2-lean steelmaking, a detailed evaluation and comparison with existing steelmaking technologies was conducted within the scope of this work.

Regarding the environmental impact of the considered production routes DR(CH_4)/EAF provides the possibility for a first reduction step in CO_2-emissions. In order to reach the above-mentioned goals, the implementation of hydrogen is indispensable. The overall CO_2-footprint of DR(H_2)/EAF depends significantly on the CO_2-intensity of the electricity used for hydrogen and steel production. Only if the system fully operates with renewable electricity, the goals for a substantial CO_2-abatement can be reached. This implicates a deep decarbonization of the electricity sector as one of the prerequisites for green steelmaking.

Another major issue which has to be considered for the transition to hydrogen-based steelmaking is a drastically increased electricity demand which will therefore be required. Additionally 340 TWh will be needed for EU 28 which corresponds to 18 % of the current EU total consumption [10]. In combination with the fact that these amounts have to be covered by renewable electricity a huge challenge for all involved stakeholders has to be tackled in future. Furthermore, the technological development and up-scale of electrolyzers is crucial for the realization of hydrogen-based steelmaking.

In order to accomplish the evaluation a detailed analysis of the cost structure was performed. In general, production costs of the DR(H_2)/EAF route are ~35 % higher than for the BF/BOF or DR(CH_4)/EAF route. One of the main influencing factors on the BF/BOF production costs are the prices for CO_2 whereas the costs of the hydrogen-based process is substantially dependent on electricity prices. This means, that for an economic viable realization of hydrogen-based steelmaking, either low electricity prices or, contrarily, higher prices for CO_2-emissions are required.

To sum up, the evaluation shows that the DR(H_2)/EAF process can be identified as promising option for the decarbonization of the steel industry if some important prerequisites such as the up-scale of the electrolyzer technology, advantageous price conditions for CO_2 and electricity as well as the supply of sufficient amounts of renewable electricity are fulfilled.

References

[1] EUROFER, „European Steel in Figures 2020“, 2020.

[2] Worldsteel, „Steel Statistical Yearbook 2019“, World Steel Association, 2019.

[3] Midrex, „World Direct Reduction Statistics“, 2019.

[4] EUROFER, „A steel roadmap for a low carbon Europe 2050“, 2013.

[5] EUROFER, „Low Carbon Roadmap. Pathways to a CO_2-neutral European Steel Industry“, 2019.

[6] EUROFER, „https://www.eurofer.eu/“, [Online]. [Accessed 01 12 2020].

[7] EUROFER, *Map of EU steel production sites,* 2019.

[8] J. Wiencke et al., „Electrolysis of iron in a molten oxide electrolyte“, *Journal of Applied Electrochemistry,* 48, 2018, pp. 115-126.

[9] D. R. Sadoway, *Sustainable Steelmaking by Molten Oxide Electrolysis,* LowCarbonFuture Webinar, 2019.

[10] A. Eggert, *European steel industry pathways towards the smart, low carbon and competitive industry of the future,* EU Industry Days, Brussels, 2018.

[11] M. Seftejani et al., „Reduction of Haematite Using Hydrogen Thermal Plasma“, *Materials,* 12, 2019, p. 1608.

[12] A. Ito et al., „The future of steelmaking – How the European steel industry can achieve carbon neutrality“, Roland Berger GmbH, 2020.

[13] K. Rechberger et al., „Green Hydrogen for Low-Carbon Steelmaking“ *4th ESTAD*, Düsseldorf, 2019.

[14] J. Ripke, „Direct from MIDREX. 3rd Quarter 2017“, 2017.

[15] J. Madias, „Electric Furnace Steelmaking“, *Treatise on Process Metallurgy,* vol. 3, 3, 2014, pp. 271-300.

[16] M. Kirschen et al., „Influence of direct reduced iron on the energy balance of the electric arc furnace in steel industry“, *Energy,* vol. 36, 10, 2011, pp. 6146-6155.

[17] E. Nyankson et al., „Kinetics of Direct Iron Ore Reduction with CO-H_2-Gas Mixtures“, *IJERT*, 2015, pp. 934-940.

[18] K. Rechberger et al., „Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking“, *Steel Research International*, vol. 91, 11, 2020, pp. 1-10.

[19] P. Dahlmann et al., „Steel Roadmap for Low Carbon Europe 2050 - Technical Results“, *4th ESTAD*, Düsseldorf, 2019.

[20] M. Wörtler et al., „Steel`s Contribution to a low-carbon Europe 2050“, Boston Consulting Group, 2013.

[21] P. Cavaliere, "Ironmaking and Steelmaking Processes - Greenhous Emissions, Control and Reduction", Switzerland: Springer, 2016.

[22] N. Müller et al., "Assessment of the transition from coal-based steelmaking to hydrogen-based steelmaking", *4th ESTAD*, Düsseldorf, 2019.

[23] B. Rammer et al., „Comparing the CO_2 Emissions of Different Steelmaking“, *BHM*, 162, 2017, pp. 7-13.

[24] R. Remus et al., „Best Available Techniques (BAT) Reference Document for Iron and Steel Production“, European Commission's Joint Research Centre, 2013.

[25] European Environment Agency, „https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-5#tab-googlechartid_chart_11_filters=%7B%22rowFilters%22%3A%7B%7D%3B%22columnFilters%22%3A%7B%22pre_config_ugeo%22%3A%5B%22European%20Union%20(current%20composition)%22%5D%7D%7D“, [Online]. [Accessed 01 09 2019]

[26] Worldsteel, „Energy use in the steel industry“, 2016.

[27] M. Hölling et al., „Bewertung der Herstellung von Eisenschwamm unter Verwendung von Wasserstoff“, *StahlEisen,* vol. 47, 2017, p. 137.

[28] M. Weigel, „Ganzheitliche Bewertung zukünftig verfügbarer primärer Stahlherstellungsverfahren. Einschätzung der möglichen Rolle von Wasserstoff als Reduktionsmittel“, PhD-thesis, 2014.

[29] N. Pardo et al., „Prospective Scenarios on Energy Efficiency and CO_2 Emissions in the EU Iron & Steel Industry“, European Commission, 2012.

[30] MIDREX, „Direct from MIDREX. 4th. Quarter 2019“, 2019.

[31] IEAGHG, „Iron and steel CCS study (techno- economics integrated steel mill)“, 2013.

[32] EUROSTAT, „https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_205&lang=en“, [Online]. [Accessed 12 08 2020]

[33] EUROSTAT, „http://appsso.eurostat.ec.europa.eu/nui/show.do?query=BOOKMARK_DS-052782_QID_-53DAAB67_UID_-3F171EB0&layout=TIME,C,X,0;GEO,L,Y,0;PRODUCT,L,Z,0;CONSOM,L,Z,1;UNIT,L,Z,2;TAX,L,Z,3;CURRENCY,L,Z,4;INDICATORS,C,Z,5;&zSelection=DS-052782CONSOM,4162903;DS-052782I“, [Online]. [Accessed 12 08 2020]

[34] EEX, „https://www.eex.com/en/markets/environmental-markets/emissions-auctions“, [Online]. [Accessed 20 10 2020]

[35] International Energy Agency, „World Energy Outlook 2018“, 2018.

[36] J. Mayer et al., „Macroeconomic implications of switching to process-emission-free iron and steel production in Europe“, *Journal of Cleaner Production,* 2019, pp. 1517-1533.

[37] J. Janssen, „Hydrogen cost analysis“, 2019.

[38] M. Weeda, „WP9 Impact and Exploitation“, in *7th Steering Committee H2FUTURE*, Linz, 2018.

[39] H2FUTURE, "Hydrogen meeting future needs of low carbon manufacturing value chains", *Proposal,* 2016.

[40] MATERIAL ECONOMICS, „The Circular Economy. A Powerful Force for Climate Mitigation“, 2018.

Annex

Table 10: Hydrogen and natural gas demand for European steel production

Countries	H_2 Demand [10^6 m^3]	NG Demand [10^6 m^3]
Austria	3940	254
Belgium	3444	222
Czech Republic	2994	193
Germany	18962	1221
Finland	1786	115
France	6712	432
Hungary	1058	68
Italy	2883	186
Netherlands	4345	280
Poland	3439	221
Romania	1387	89
Slovakia	3049	196
Spain	3132	202
Sweden	1804	116
United Kingdom	3604	232
EU (28)	**62538**	**4027**

Table 11: Additional electricity demand for European steel production

Countries	Electrolyzer [TWh]	EAF [TWh]	Auxiliaries [TWh]	TOT [TWh]
Austria	19	2	1	21
Belgium	16	2	1	19
Czech Republic	14	2	0	16
Germany	90	11	3	103
Finland	8	1	0	10
France	32	4	1	37
Hungary	5	1	0	6
Italy	14	2	0	16
Netherlands	21	3	1	24
Poland	16	2	1	19
Romania	7	1	0	8

Slovakia	14	2	0	17
Spain	15	2	0	17
Sweden	9	1	0	10
United Kingdom	17	2	1	20
EU28	**295**	**36**	**9**	**21**

Table 12: Process-related CO_2 emissions from BF/BOF, DR(CH_4)/EAF and DR(H_2)/EAF

Process	Direct CO_2 [kg/t CS]	Upstream CO_2 [kg/t CS]	TOT CO_2 [kg/t CS]
BF/BOF	1827	99	1926
DR(CH_4)/EAF	516	116	632
DR(H_2)/EAF	163	115	278

Table 13: Influence of the indirect emissions on the total amount of CO_2 emitted.

Process	Units	Electricity carbon-intensity					
		0 gCO_2/ kWh		295.8 gCO_2/ kWh		500 gCO_2/ kWh	
		Indirect	TOT	Indirect	TOT	Indirect	TOT
BF/BOF	kg/t CS	0	1926	39	1965	66	1992
DR(CH_4)/EAF	kg/t CS	0	632	137	770	232	865
DR(H_2)/EAF	kg/t CS	0	278	1028	1307	1738	2016