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Green Hydrogen

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Author(s)	Amaia Sasiain Conde, – K1-MET GmbH
Reviewers	Hermann Wolfmeir, Chris Harris – voestalpine Stahl GmbH Marcel Weeda, TNO

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Executive Summary

This study was carried out as part of Task 9.4 and analyses the rollout of the project results for the decarbonization of the steel industry. To accomplish this task, the results of deliverable 9.1 concerning the hydrogen and energy requirements to achieve a low carbon steel industry through the shift of the steel production towards the direct reduction with hydrogen, which were calculated according to the PEM performance installed in Linz were used.

The techno economic analysis performed along deliverable 9.1 served as a basis for the determination of the energy and hydrogen requirements for the decarbonization of the steel industry bringing the direct reduction with hydrogen into focus.

As detailed in deliverable 9.1, 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 the hydrogen-based route, operated almost without the utilization of carbonaceous fossil sources. Nevertheless, the hydrogen 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 corresponding energy and hydrogen requirements calculated in deliverable 9.1 for the decarbonization of the European steel industry via the direct reduction with hydrogen using electrolytic hydrogen, were contrasted with the projects and plans announced by different European steel stakeholders, intended to decrease the CO_2 emissions in the iron and steel sector in order to get an overview of the trajectory of the European steel industry towards its decarbonisation. The large number of hydrogen-related initiatives found across Europe was first screened and only those project proposals where steel stakeholders and the element hydrogen were involved, were considered. Those proposals were then rearranged with attention to the type of process used, planned start date, production capacities, project partners involved and location.

The evolution until commercial operation of low carbon production routes and the availability of enough green hydrogen to cover steel production are two important boundary conditions for the rapid development of a low carbon steel industry using hydrogen. For this reason, planned activities for the development of electrolysis capacities in Europe, were as well investigated during the accomplishment of this report. Although the existence of relevant infrastructure for the delivery of the hydrogen produced to the required points and the availability of enough renewable capacities across Europe are as well important requirements to achieve a hydrogen-based steel industry, these topics are beyond the scope of this report.

Table of Contents

List of Figures

List of Tables

1 Introduction

Work Package 9 (WP 9) of H2FUTURE is provided by four working areas and related tasks to cover the impacts of the project results and exploitation:

- Task 9.1.: Performances of the electrolyser system
- Task 9.2.: Scaling and replication of the H_2 generation electrolysis process for the steel industry in EU 28
- Task 9.3.: Scaling and replication of the H_2 electrolysis 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 Scope of the Document

The scope of this document is to present the rollout of the PEM-electrolysis technology as a key factor for the decarbonization of the European steel industry. The development of this rollout is based on technical and economic conditions numerically described as CAPEX and OPEX (already defined and reported in Deliverable 9.1) as well as on projections based on installed capacity, renewable energy potential for each European member state. Additionally, the supplementary requirements for the steel industry to reach the net zero emission goal launched by the European commission by 2050 are highlighted in this report.

Notations, Abbreviations and Acronyms

Table 1: List of acronyms

PEM	Polymer Electrolyte Membrane / Proton Exchange Membrane
BF	Blast Furnace
BOF	Basic Oxygen Furnace
WP	Work Package
CAPEX	Capital Expenditures
OPEX	Operational Expenditures
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
GHG	Greenhouse Gas
EAF	Electric Arc Furnace
DR	Direct Reduction
DRI	Direct Reduced Iron
HBI	Hot Briquetted Iron
CDRI	Cold Direct Reduced Iron
CS	Crude Steel
NG	Natural Gas
HPSP	Hydrogen Plasma Smelting Reduction
EPRS	European Parliament Research Service

2 Achieving net zero emissions by 2050

2.1 Low carbon production processes in the steel industry

The European steel industry produced 167.7 million tonnes [1] of steel in 2018 at more than 500 production sites across 22 EU member states [2] (see Table 3 from Annex). As shown in Figure 1, 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 58.5 % and 41.5 % of the EU28 steel production respectively [1].

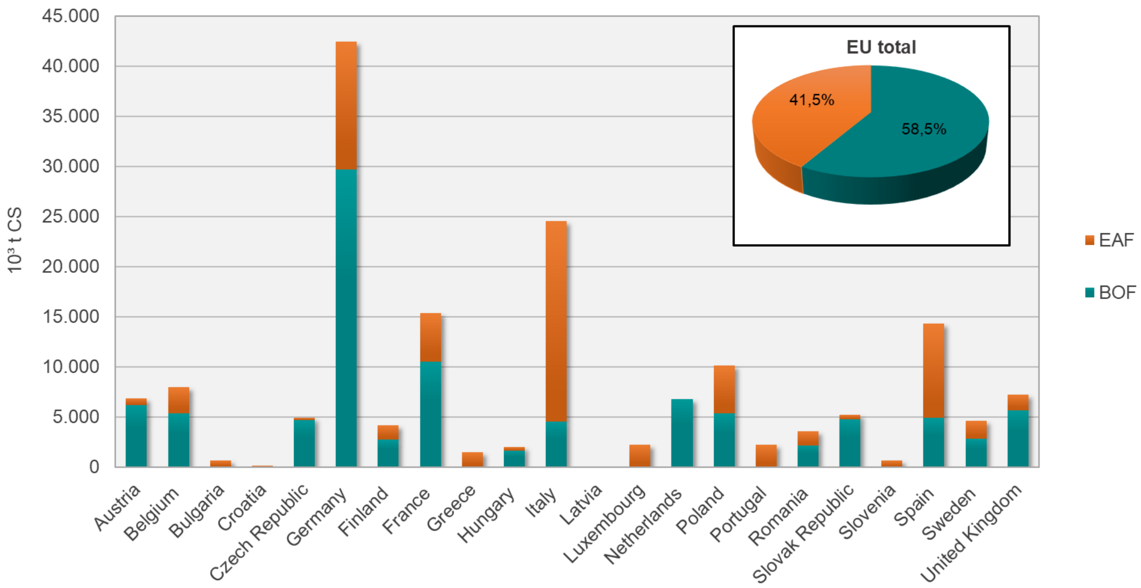

Figure 1: Current steel production amounts depending on process [1]

The production of direct reduced iron (DRI) comprises a minor part of the overall steel production, as it is limited to specific regions where natural gas can be purchased at a relatively low-cost price.

As the production of steel from iron ores is currently closely linked to the element carbon, it is consequently highly dependent on fossil fuels resulting in large amounts of CO_2 emissions. Considering the implementation of best practices, 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 current production routes (BF/BOF, scrap-based EAF) presented in Figure 1 is about 15% [3]. Despite the lower carbon footprint of the scrap-EAF route, natural iron sources as raw material will still be required in the future due to the limited availability of scrap of sufficient quality.

Through the UN's Paris Agreement of 2015 and its own Green Deal in 2019, the European Union has committed to become climate neutral by 2050. Additionally, the European Commission has announced an interim reduction target in CO_2 emissions of 55% by 2030, compared to 1990 levels. This goal deeply relate to the European steel industry, as one of the biggest industrial emitters of CO_2. According to a publication launched by the European Commission in 2021 [4], 221 million tonnes of greenhouse gas (GHG) emissions are currently emitted by this sector, which corresponds to 5.7% of the total CO_2 emitted in Europe.

Reaching the objectives for 2030 and 2050 will not be possible without the use of the so-called “breakthrough technologies”.

As presented in Deliverable 9.1, among the low carbon steel production routes, the direct reduction or ores with hydrogen appears as one of the paths with the most promising perspectives. As depicted in Figure 2, due to its high technology readiness (TRL), direct reduction with hydrogen is a perfect candidate for relatively short term implementation in comparison with other technologies which may require longer to reach technology maturity.

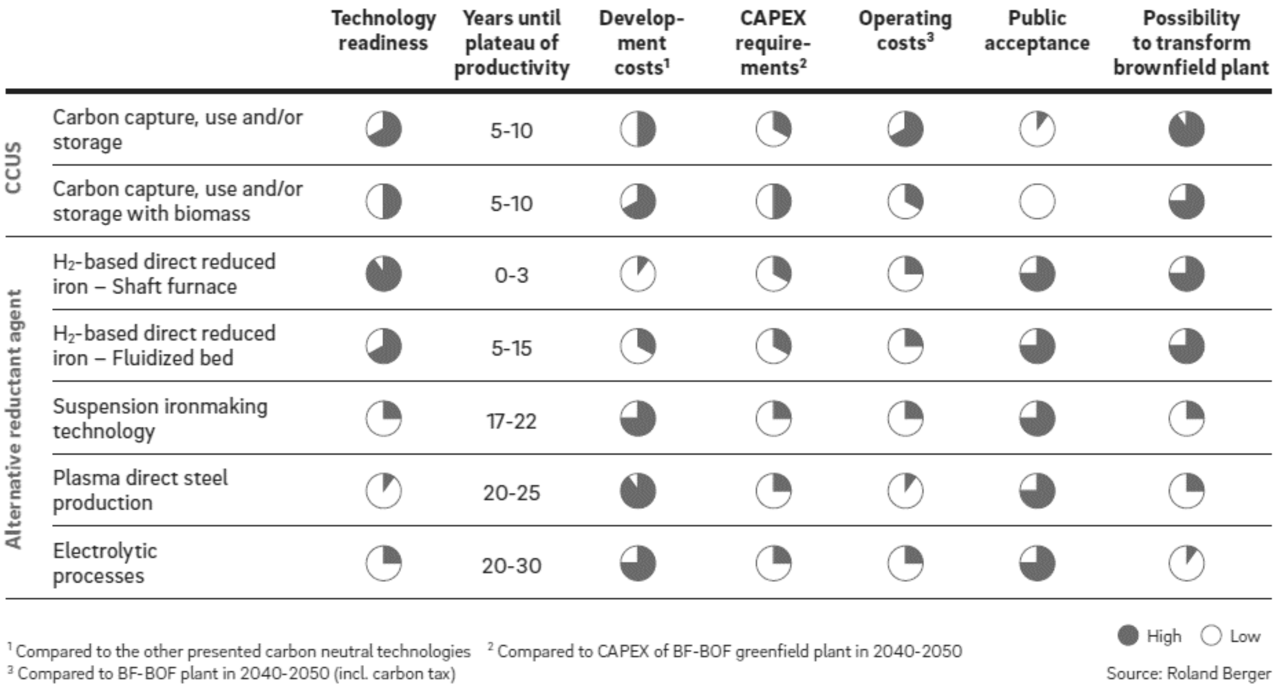

Figure 2: Comparison of CO_2-mitigation technologies [5]

2.2 Direct reduction with hydrogen

The direct reduction in conjunction with EAF is a well-established process, usually operated with natural gas. Natural gas-based direct reduction DR(CH_4) could be utilized as an entry point for the DR(H_2), since it provides the possibility for injecting hydrogen as reducing agent as well as to run the process only with hydrogen as already mentioned in Deliverable 9.1. This is possible because the DR(CH_4) process already operates with a certain amount of hydrogen as reducing gas, since the natural gas must be previously reformed to syngas (H_2 and CO). For example, in the case of the MIDREX® process, the syngas coming from the reformer, contains about 55 % of hydrogen and 35 % of carbon monoxide, being the remaining 10% composed by H_2O, CO_2, CH_4 and N_2 [6].

Following the information given by Ripke et al. [7] about 30 % of the natural gas in the MIDREX® process can be replaced by hydrogen without any major process changes. Nevertheless, for an increased addition of hydrogen, various factors which impact the operation of the DR-process have to be taken into account, since the gas amounts increase and different process conditions have to be considered in the shaft furnace. Different gas flows, residence times and operating conditions could affect the chemical reactions taking place in the furnace. Gas compositions and temperatures as well as the metallization degree could be affected because of the change of reducing agents [8]. For this reason, for a hydrogen injection over approximately 30%, certain process modifications must be implemented, as for example the exchange of the reformer for a gas heater.

According to the calculations performed in Deliverable 9.1 the usage of hydrogen in the direct reduction process is limited to 95%, as a certain share of natural gas is still required to maintain the temperature of the process and the carbon content of the DRI. The flowsheet of the system configuration of a DR(H_2) process, is depicted in Figure 3. The reformer, characteristic of the Midrex® DR(CH_4) process, is exchanged by a gas heater which will be attached to the system to preheat the gases to the required temperature. Either hydrogen or other environmentally friendly heat sources might be used as fuel for the heater.

In the direct reduction process, oxygen is removed by reacting with hot reducing gas (CO and H_2, for DR(CH_4)) in the shaft furnace and unlike the BF, the DR-processes operate without any liquid metal or slag phase.

For the direct reduction with natural gas, the oxygen from the iron ore reacts with the CO and H_2 at elevated temperatures to produce metallic iron while releasing CO_2 and H_2O, according to simplified Eq. (1) and (2).

$$Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe + 3\ H_2O \qquad \Delta H = 99\ kJ/mol \qquad (1)$$

$$Fe_2O_3 + 3\ CO \rightarrow 2Fe + 3\ CO_2 \qquad \Delta H = -24kJ/mol \qquad (2)$$

When using H_2 as the main reducing agent, a higher reduction degree from iron ore to iron is achieved [9]. However, the reduction process is thermally unfavorable, due to the endothermic nature of the reaction between hydrogen and iron oxide (see Equation 1).

In the case of the MIDREX® DR(CH_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 the processed “top gas” returns 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(CH_4)-process.

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. For the DR(H_2), part of the top gas is used as fuel for the heater, which is emitted via the stack to avoid enrichment of nitrogen and other impurities in the system, (see Figure 3).

The hot DRI produced can either be fed right into the EAF, briquetted to hot briquetted iron (HBI) or cooled and used as cold DRI (CDRI). 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. 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, causing the charged materials to melt faster. 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 [7]. Natural gas and CO help to maintain the desired carbon content, as described 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. 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 fluxed via lime addition, which can increase 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 [10]. 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 [11].

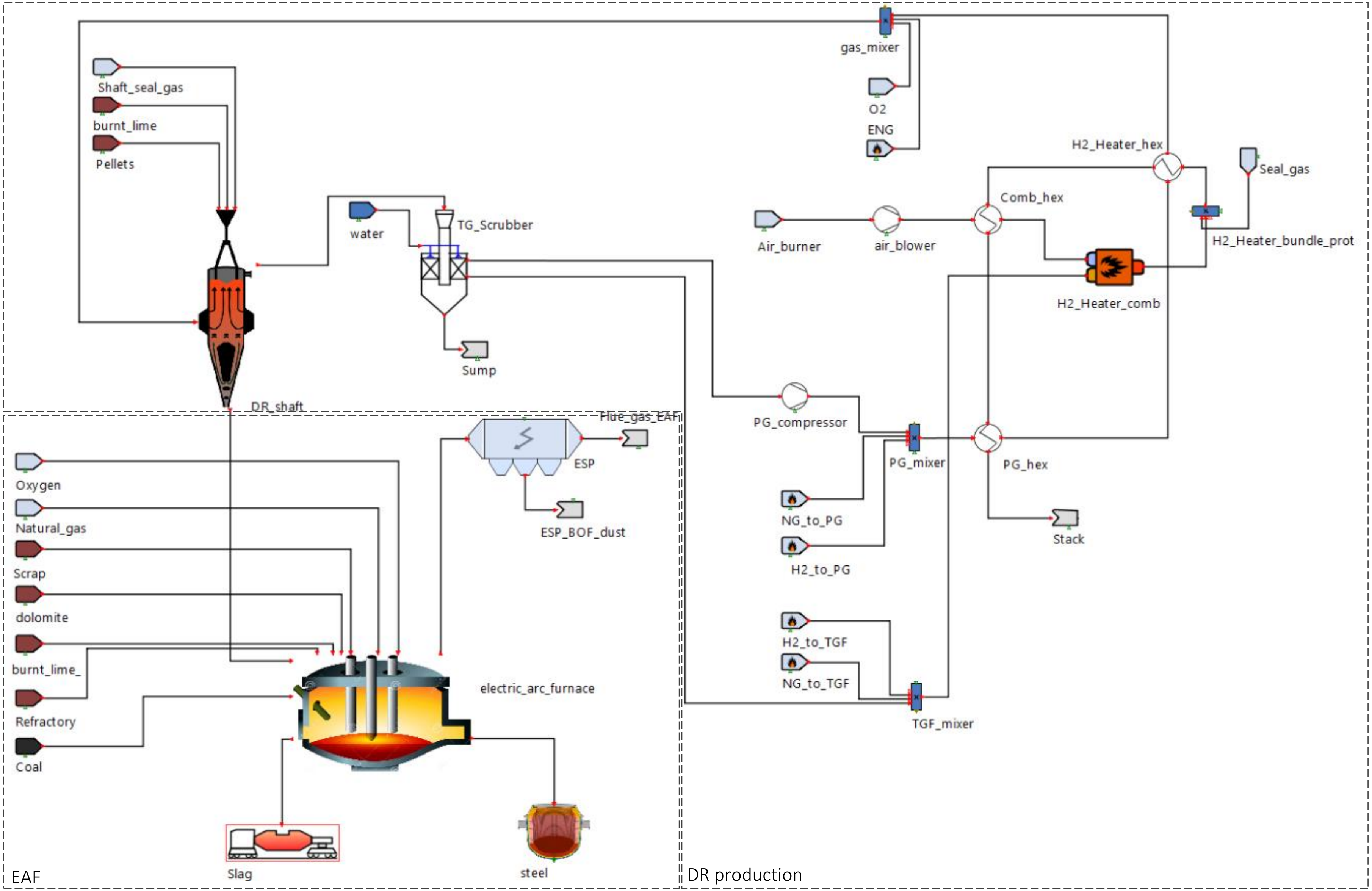

Figure 3: Process scheme and system boundaries of DR(H_2)/EAF process

2.3 Energy and hydrogen demand for the decarbonization of the steel industry

The transformation towards a lean carbon steel industry is intimately linked to a shift of the energy demand. Due to the lack of literature data, high level calculations were performed in Deliverable 9.1 in order to calculate the energy and hydrogen demand for a complete shift to a green steel industry. As previously explained in section 2.1, due to the promising near future projections of the direct reduction with hydrogen, the fully implementation of this process across Europe was assumed for the calculations. Since it was considered that the hydrogen demand for the direct reduction would be covered by electrolysis, the hydrogen requirements and its corresponding energy costs to achieve net zero emissions in the iron and steel sector were calculated. As explained in Deliverable 9.1, the current crude steel production via the BF/BOF route was used as basis for the calculations, as it is the predominant primary production process and additionally has the highest CO_2 footprint.

Since a certain amount of NG is still needed in the $DR(H_2)$ process to maintain the process temperatures and the carbon content of the produced DRI, the corresponding NG requirements were as well calculated. The hydrogen and natural gas demands for every European country to achieve the full transformation of the steel industry are depicted in Figure 4. The complete shift of the steel produced via the BF/BOF route to the $DR(H_2)$/EAF will lead to an overall hydrogen demand for the EU28* of 62.5 billion m³/a or 5.6 million t/a respectively, and an additional amount of 4 billion m³ of natural gas (see Table 4 from Annex).

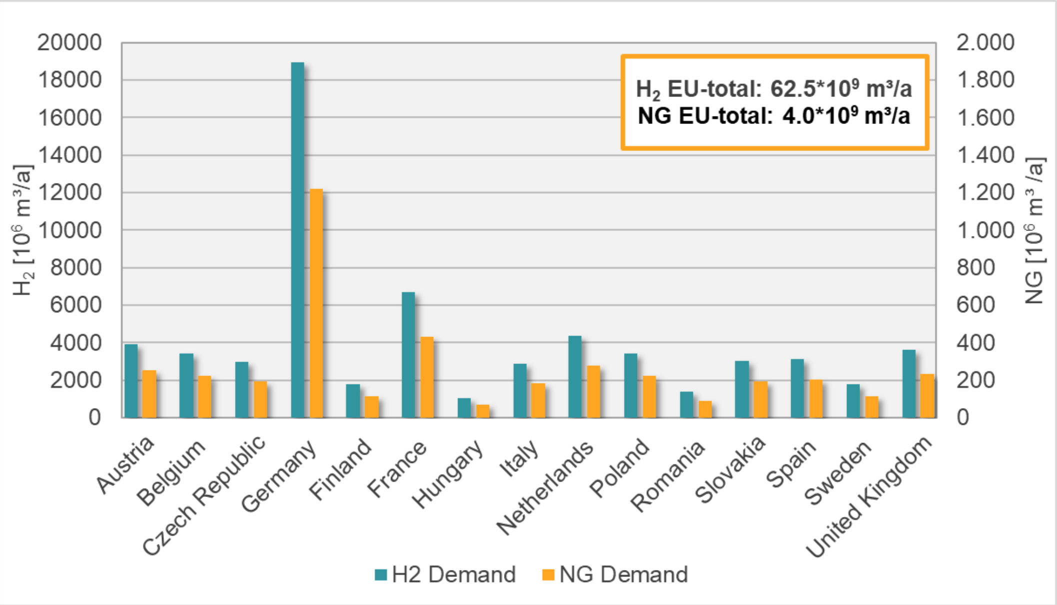

Figure 4: Hydrogen and natural gas demand for European steel production

* For consistency throughout the entire project duration, The United Kingdom is included in the analysis

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

As explained above, the energy requirements linked to the hydrogen production and the direct reduction process itself were as well calculated for every European country (see Figure 5; Table 5 from Annex), as the utilization of hydrogen will lead to an increase in the European electricity demand. The energy requirements for the hydrogen production, were calculated according to the results delivered from the PEM electrolyser installed in Linz as part of the H2FUTURE project.

Considering that approximately 300 TWh/a are needed to fulfill the energy requirements for the electrolyser, a total additional electricity demand of around 340 TWh/a will be required for EU 28 when adding the electricity needed for the EAF- and DR-process itself, which corresponds to 18 % of the current EU total consumption [12]. Whereas approximately 80-125 kWh/t DRI are necessary to cover the electricity demand for auxiliaries (compressors, water supply, etc.) [13], [14], the EAF requirements will be in the range of 310-640 kWh/t CS, depending on the share of scrap/DRI, temperature of DRI, specific slag mass etc., as previously indicated [15].

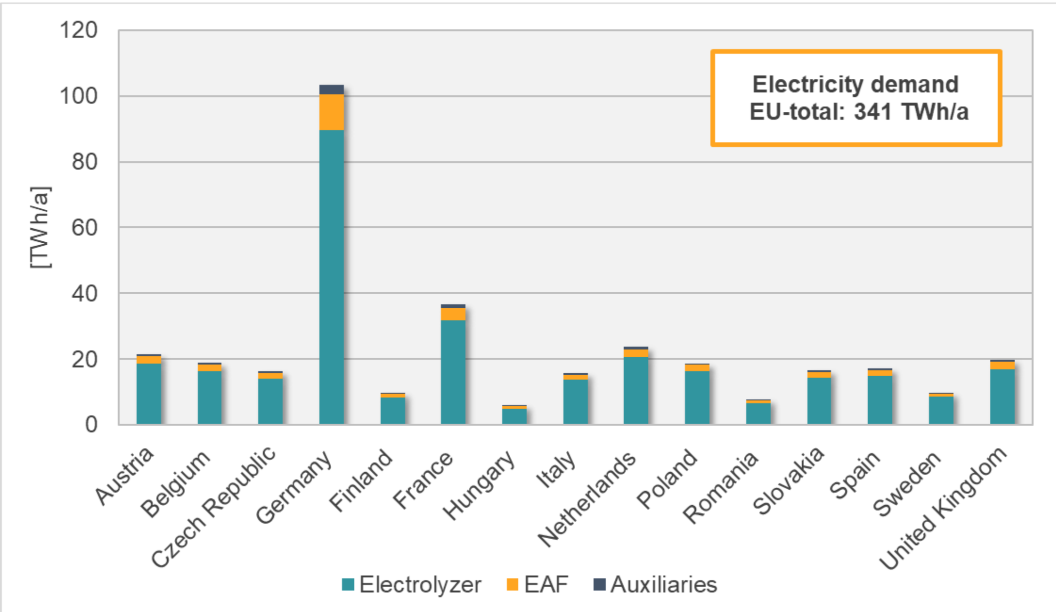

Figure 5: Additional electricity demand for European steel production

3 EU project scheme overview

3.1 Low carbon projects in the steel industry

After outlining the hydrogen and energy requirements for the decarbonization of the steel industry, the current status of decarbonization pathways for the next decades in the different European countries was examined. This results in an overview of existing activities and the needs to achieve net zero emissions by 2050. For this purpose, extensive research was performed in order to obtain a picture of the plans from the European steel stakeholders for the upcoming years (see Table 6-Table 16 from the Annex). Information regarding projects directly or indirectly related with the decarbonization of the steel industry was collected under 2 premises: (I) the inclusion of the element hydrogen and (II) the participation of steel players. It must be highlighted that the information compiled, does not necessarily include the entire initiatives prospected until 2030 or 2050, as certain proposals were confidential or under development at the time of writing of this document. For this reason, the data gathered here only refer to the projects or project proposals published so far. The goal of this part of the report is to provide an overview of the magnitude of the projects and the trend of the different countries concerning the decarbonization of the iron and steel sector.

Figure 6. Map of hydrogen initiative in Europe under the steel industry framework

It was observed that the timeframe for the vast majority of the projects or project proposals was delimited until 2030 and very few projections by 2050 were noted.
In the map above, the initiatives found for the European Union (Figure 6) are depicted. The map tries to offer a general outlook of the European hot spots with hydrogen projects connected to the decarbonization of the steel industry. It is observed that the "hot spots" here depicted, coincide with the nerve centers of steel production (Figure 7)

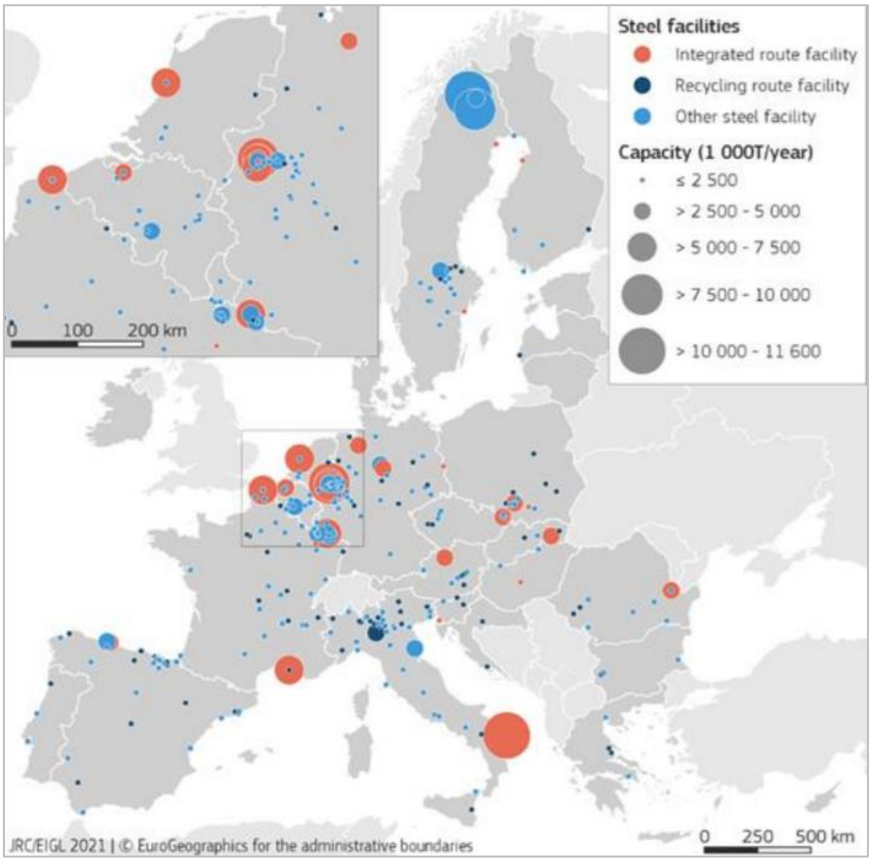

Figure 7. Steel manufacturing facilities in the European Union [4]

When looking at the various proposals (see Table 6 - Table 16 from the Annex) launched by the different European countries and focusing exclusively on those initiatives linked to the direct avoidance of carbon release, the direct reduction process with hydrogen emerges as the main trend among the projects listed. On the second position, are highlighted the reduction of iron ore fines in a fluid state using hydrogen, or the hydrogen plasma smelting reduction. These initiatives seem to be in a lower state of development (lower TRL) and show lower production capacities in general: between 100 kg and 800 kg, whereas production ranges of DR(H_2) projects fluctuate between 2500 kg DRI/day and 5Mt /y of steel.
As mentioned several times in this report, the direct reduction route with hydrogen seems to be one of the processes with best prospects for a rapid development during the coming years, which is confirmed by this outlook showing a trend in the steel industry towards direct reduction.
A study recently published [16], shows that in order to cut off 30% of the CO_2 emissions produced by the iron and steel industry by 2030, at least 29 Mt of steel produced via the primary route should be transformed into low carbon production processes (Under the assumption that the amount of crude steel produced by 2030 remains the same as current production).

Figure 8, reflects the low carbon steel production capacities projected until 2030. As depicted, the maximum total crude steel production planned for 2030 is around 22Mt/CS per year, which differs from the 29Mt/y necessary to fulfil the CO_2 reduction objectives for 2030.

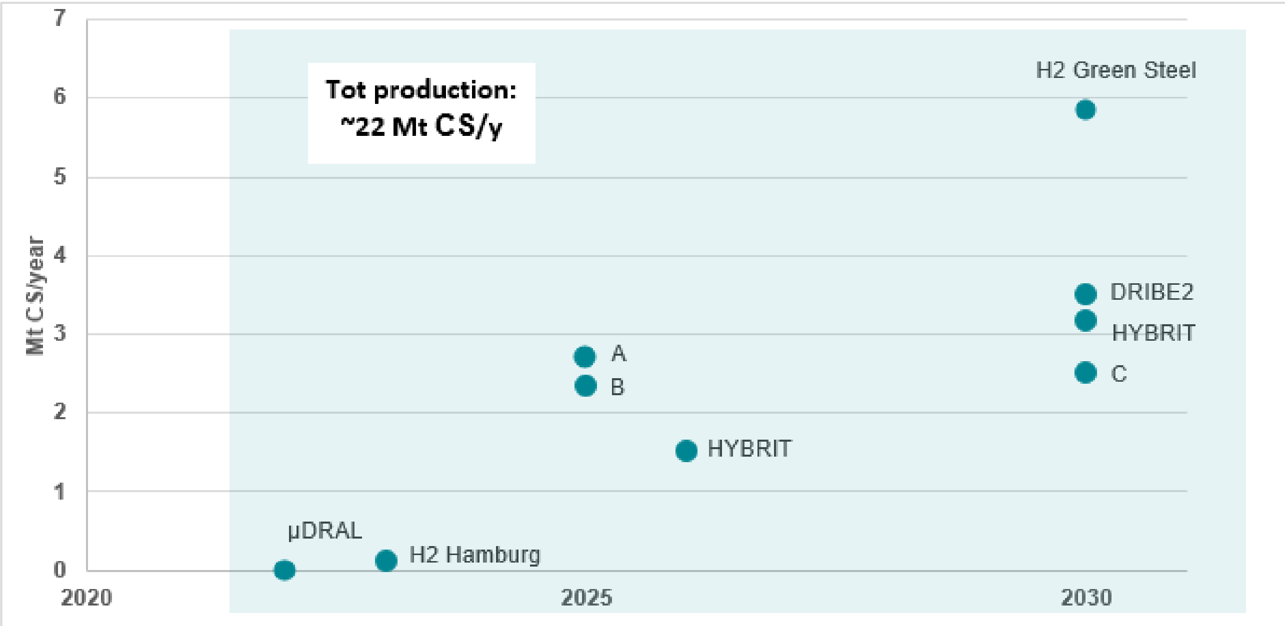

Figure 8. Production capacity prospections until 2030 in EU *

However, it should be taken into consideration, that more projects might be proposed during the following years, a fact which could speed up the development of this low carbon technologies. Additionally, it must be remarked, that the achievement of this 30% CO_2 reduction can be as well supported by the improvement of other processes inside the steel mill which can diminish the CO_2 footprint of the integrated route.

To break up the carbon cycle and achieve the net zero emission reduction for 2050, breakthrough technologies are needed. For this reason, the projects taken for Figure 8 are exclusively focused on processes which produce steel without the release of CO_2. Additionally, only those projects with a projected production capacity upon 1000 t/y were taken into account. Projects in their first research stages which consequently offer lower production capacities were omitted, considering as a result only those projects close to commercial operation and thus capable to produce large quantities of steel.

In order to make a proper comparison between the different production capacities published by the diverse project proposals framed in Figure 8, a few calculations were performed as the production capacities gathered were labelled as tonnes of steel per year and tonnes of DRI per year. For this reason, the corresponding amounts of DRI were recalculated into crude steel (CS). According to the simulations performed in Deliverable 9.1, for every tonne of crude steel produced, 855,5 kg of DRI are needed (considering an addition of 25% of scrap in the EAF). Additionally, "tonnes of steel" were considered as "tonnes of crude steel". In the specific case of the project µDRAL, where a daily

* The names of the projects: "A", "B", "C" at the time of writing this report were not known

production of 2500 kg is planned, a continuous production through the year was estimated, achieving approximately 900 tDRI/y.

3.2 Development of electrolysis capacity

The decarbonization of the steel industry towards the hydrogen-based production entails the consumption of additional amounts of green electricity for the production of hydrogen. The need of large amounts of electricity is however, a common denominator for almost all low carbon steel production processes, as for example the hydrogen plasma smelting reduction (HPSP), electrolysis of iron ores, etc. According to the calculations performed through this report and as mentioned in the chapter above, this amount of electricity amounts to approximately 340TWh/a for the complete decarbonization of the European steel industry via the direct reduction with hydrogen. Making a breakdown of this figure, 45 TWh/a would be intended for the operation of the EAF and the auxiliaries (such as compressors, water supply, etc.) and the remaining 295 TWh/a would be the energy requirements calculated for the electrolyser, using the results of the project H2FUTURE. Considering the possibility to produce hydrogen uninterruptedly, around ~33GW of electrolysis capacity should be available to accomplish this shift.

The energy requirements for the DR(H_2)/EAF process route might be optimized to a certain extent if other environmentally friendly heat sources (green electricity, waste heat etc.) are used as fuel for the heater of the DR-plant. For the calculations so far the usage of hydrogen was considered for the reduction of iron oxides in the shaft furnace and as well as fuel to heat up the reduction gas in the heater.

In order to determine whether the electrolysis capacities match the hydrogen necessities from the steel industry for a complete shift of the primary steel production (mainly BF/BOF based) towards a direct reduction with hydrogen supported by electric arc furnaces, the projected targets or initiatives planned for the upcoming decade were collected and summarised. Table 2 shows the ambitions from the different European countries regarding to their planned electrolysis capacities until 2030. As seen in Table 2, the projections differ depending on the literature sources. According to the hydrogen plans launched from different European countries, gathered by IRENA [17] and IEA [18], the electrolysis capacities for EU 28, are estimated on around 45 GW , whereas other sources consulted showed values between 13 – 56 GW [19] or 0,4 -14 GW [18]. Portugal, Netherlands, Spain, Italy, Germany, France, UK, Belgium, and Austria seem to be the countries with highest ambitions for electrolysis capacities by 2030.

Leaving aside the large variations presented within the different sources consulted, the general trend of increasing electrolysis capacity is apparent. However, the question is if the necessary electrolysis capacities will be available in the right time to push the decarbonization of the steel sector, since as green hydrogen becomes available, it will not only be required for the decarbonization of the steel industry, but it will have to be shared among other consumers which also need to reduce its own CO_2 emissions as the as the transport sector, power generation or other hard to abate industry sectors.

Table 2. Projected targets / initiatives electrolysis capacity for 2030

Country	Electrolysis capacity [GW]		
	[17]	[19]	[18]
Poland	2	0,7 - 1,8	
Portugal	2,3	0,3 - 2,7	
Netherlands	3,5	0,8 - 3,6	0,2 - 7,0
Spain	4	1,0 - 4,1	
Italy	5	1,3 - 6,7	
Germany	5	3,0 - 13,7	0,1- 2,0
France	6,5	1,2 - 5,3	0,05 - 1,0
UK	5 [18]	1,1 - 5,6	0,02- 4,1
Ireland		0,0 - 0,3	
Belgium		0,4 - 2,3	
Austria		0,6 - 2,0	
Czech Republic		0,1 - 0,6	
Slovakia		0,1 - 0,4	
Hungary		0,3 - 0,9	
Romania		0,3 - 0,8	
Bulgaria		0,3 - 0,5	
Greece		0,4 - 1,0	
Denmark		0,1 - 0,6	
Sweden		0,4 - 1,2	
Finland		0,3 - 1,1	
Estonia		0,005 - 0,05	
Cyprus		0,01- 0,1	
Croatia		0,03 - 0,2	
Slovenia		0,02 - 0,1	
Latvia		0,02 - 0,1	
Lithuania		0,04 - 0,3	
Luxemburg		0,1 - 0,3	
Malta		0,003 - 0,03	
EU remaining capacity	11,8		
EU 28	**45**	**13 - 56**	**0,4 - 14,0**

4 Transition towards net zero emissions for the steel industry

Several reports have been written during the last years regarding the possible future pathways for the decarbonization of the steel sector. To a greater or lesser extent hydrogen appears as an important and determining element for the reduction or near total elimination of the carbon emissions in the steel industry, which is illustrated by the plenty project proposals launched by different steel stakeholders, commented in the chapter above and shown in the Annex.

Despite diverse decarbonization strategies being described in the different reports reviewed, all of them showed that hydrogen plays a fundamental role for the decarbonization of the iron and steel sector. In line with the initiatives seen in the Annex and according to the European Parliamentary Research Service (EPRS), it is expected that the production of steel through the direct reduction with hydrogen route may reach commercialization at large capacities as early as 2035.

Whereas some studies present the DR(H_2)/EAF as the main alternative to the BF/BOF for the production of low carbon steel by 2050, as the report written by Wang et. al [20], other studies predict that technologies using 100% green hydrogen could be responsible for 40%–55% of primary steel production in 2050 whereas the rest of the primary steel production will be carried out through a selection of other low carbon production routes as for example DRI/BOF [21]. In any case, the direct reduction with hydrogen emerges as one of the predominant primary steel production routes for 2050.

Beyond the direct reduction path, in a first stage using NG and then replacing it with hydrogen, other alternatives which require lower investments seem to be attractive in the short term. This fact might push steel producers to focus on other processes as top gas recovery, carbon capture, H_2 injection, etc to progressively reduce carbon emissions, before moving to other processes as the direct reduction with hydrogen [22].

Nevertheless, retrofitting existing (BF / BOF) facilities may not be a competitive long-term strategy, when the cost of green electricity and in turn the costs of hydrogen decreases. Additionally, those alternatives present a maximum CO_2 reduction potential. According to a recent report published by Mission Possible Partnership [21], even in locations with favourable access to CO_2 sequestration sites and industrial clusters for CO_2 utilisation, hydrogen-based steelmaking may still be the more competitive option if green hydrogen can be delivered below 1–2 €/kg.

5 Conclusions

There are a number of options for steelmakers to reduce part of their existing carbon , for example through energy efficiency improvements and process changes, such as top gas recycling, switching to feedstocks/reductants with lower emissions as for example biogas, or even shifting to processes with lower-emissions, as direct reduction with natural gas. These options allow for a reduction in carbon emissions, but not all the CO_2 emissions can be avoided. Therefore, breakthrough technologies, as the direct reduction with hydrogen, with a minimal carbon footprint or carbon capture technologies are required to achieve the net zero emissions by 2050. Nevertheless, the Mission Possible Partnership [21], showed that even in locations with favourable access to CO_2 sequestration sites hydrogen-based steelmaking may still be the more competitive option if green hydrogen can be delivered at economical prices. Low-cost hydrogen plays a key role in the decarbonisation of the steel sector. Ultimately, its production relies on low-carbon electricity that is available cheaply in the long term.

DR(H_2)/EAF process can be identified as promising option for the decarbonization of the steel industry if important prerequisites such as the scale up of the electrolyser technology, advantageous price conditions for CO_2 and electricity, as well as the availability of sufficient amounts of renewable electricity and availability of the corresponding infrastructure are fulfilled.

Additionally, the growth of hydrogen-based steelmaking could help to reduce the production costs of green hydrogen in terms of CAPEX, promoting its usage in other industrial applications where direct electrification is challenging.

Nevertheless, according to a latter press release from the European steel association (EUROFER) of the 16th of December form 2021 [23], the decarbonization plans of the steel industry are in a difficult position due to the increase of the gas and electricity prices which have been growing four to five times in comparison with last year. Moreover, electricity fees have been affected by the increase of the price of CO_2 emission allowances, which were above 80 euros at the time of writing this report. For this reason, EU Leaders must ensure the achievement of the climate goals on a cost-effective manner and at the same time preserve the viability of strategic industrial sectors, as the iron and steel industry.

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Annex

Table 3: Total production of crude steel and crude steel production assets across EU28

EU-28 Countries	Number of BF & BOF [24]	Number of EAF [24]	CS production BOF [Mt] [1]	CS production EAF [Mt] [1]	CS production total [Mt] [1]
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)

Table 4: 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 5: Additional electricity demand for European steel production

Countries	Electrolyser [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 6. Low carbon projects foreseen in Germany*

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
DRIBE2	Commercial operation by 2030	Large-scale industrial plant for DRI /EAF will be built in Bremen and Eisenhüttenstadtat.	Production of up to 3,5 Mt steel by 2030 in Bremen and Eisenhüttenstadt		Bremen/ Eisenhüttenstadt	ArcelorMittal, EWE	[25], [26]
H2 Hamburg	Commencial operation by 2025	Test of H_2 on an industrial scale in an already existing DRI-EAF plant	Production of 100,000 t DRI/year from 2023 onwards	Sept 2019. Framework Collaboration Agreement (FCA) between Arcelor Mittal and Midrex Technologies signed to design the Hamburg demonstration plant	Hamburg	ArcelorMittal	[25], [26], [27]
Dilcos	Phase 1: 2016-2027 Phase 2: 2027-2031 Phase 3: 2031-2040 Phase 4: 2040-2050	Transformation towards "green steel" via DR(H_2/NG)			Dillingen/ Völklingen	ROGESA, Roheisengesellschaft Saar mbH, Saarstahl	[28]
tkH2Steel	2022 Second phase (H2 in BF) 2024 First large scale DR plant	Use of H_2 as reducing agent in the BF as first step to avoid CO_2 emissions. The second step involves the development of DR plants		2019 First tests (H_2 in BF)	Duisburg-Hamborn	Thyssenkrupp Steel, Air Liquide	[29]
RWE-Thyssenkrupp Duisburg steel plant	Conversion of BF by 2022	Build electrolysis capacities to supply green H_2 for the steel production.	100MW electrolyser (ALK)		Lingen	Thyssenkrupp Steel, RWE Generation	[30], [31]
HydrOxy Hub Walsum	Commercial operation by 2025	Feasibility study for the construction of a water electrolysis plant to supply green H_2 and O_2 to the nearby steel mill	500MW electrolyser (ALK)		Duisburg	Thyssenkrupp Steel, Thyssenkrupp Uhde Chlorine Engineers, STEAG	[30], [32]
GET H2		Initiative for the implementation of a nationwide H_2-infrastructure for Germany			Salzgitter	More than 30 project partners: Salzgitter Flachstahl, Thyssenkrupp Steel, Uniper…	[33]
H2SYNGAS	In operation by 2021	Use their own process gases and H_2 in the BF process (e.g., dry reforming of COG)		Scheduled for operation on summer 2021	Saar region	Saarstahl, Dillinger, Paul Wurth	[34]

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
SALCOS - WindH2	In operation by 2021	Construction of 7 wind turbines and a PEM electrolyser to gain experience with the on-site production of H_2 and its incorporation into an integrated steel mill	2MW electrolyser (PEM) 30 MW wind turbines (7)		Salzgitter	Salzgitter, Avacon , Linde	[35]
GrInHy2.0	2019- 2022	Use of waste heat from integrated steelworks for H_2 production and analysis of the potentials of renewable H2 in the iron-and-steel industry	0,72 MW electrolyser (SOEC)		Salzgitter	Salzgitter Flachstahl GmbH, Salzgitter Mannesmann, Forschung GmbH, Sunfire GmbH, Paul Wurth S.A., Tenova SpA, French research centre CEA	[32], [36]
µDRAL	In operation by 2022	Construction DRI demonstration plant to operate flexibly with NG and H_2. DRI will be first used in the BF to reduce the amount of PCI	2500 kg DRI /d		Salzgitter	Salzgitter Flachstahl GmbH, Tennova	[37]
Carbon2Chem	2018-In operation	Usage of the BFG for production of methanol, ammonia and other products	2 MW (ALK)	In operation	Duisburg	Thyssenkrupp	[30]

Table 7. Low carbon projects foreseen in Austria*

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
H2FUTURE	2017-2021	Construction 6 MW PEM electrolyser to test the suitability of green H_2 production on industrial scale to replace fossil fuels in steel production. The H_2 produced is fed into resource-optimised BF via the coke gas pipeline.	PEM electrolyser: 6MW H2 production: 1200m^3/h	2019: Commissioning 2021: Test programs running successfully	Linz, Voestalpine Stahl GmbH	VERBUND, Siemens, Austrian Power Grid, K1-MET, TNO	[38]
SuSteel Follow Up	2019-2023	Operational optimization of hydrogen plasma smelting reduction, shift from batch to semi-continuous operation, usage of N_2 instead of Ar, recirculation of H_2 and upscaling.	Batch operation 100kg iron ore	2nd quarter 2021: start of testing program	Leoben, Voestalpine Stahl Donawitz GmbH	Voestalpine Stahl GmbH, Voestalpine Stahl Donawitz GmbH, Montanuniversität Leoben, K1-MET	[39]
HYFOR	2019-2023	Build and run a pilot plant to reduce iron ore fines in a fluid state using hydrogen	800 kg HDRI	2021: Construction & commissioning of the pilot facility	Leoben, Voestalpine Stahl Donawitz GmbH	Voestalpine Stahl GmbH, Voestalpine Stahl Donawitz GmbH, Montanuniversität Leoben, K1-MET	[38], [40]
Underground Sun Storage 2030	2021-2025	Build a research facility at a depleted natural gas reservoir to test seasonal, underground storage of large volumes of green H_2. Additionally, investigation of the possible uses in energy-intensive industrial processes will be carried out.		Relevant testing will be conducted to 2025	Gampern (Upper Austria), RAG Austria	RAG, Axiom, Energie AG, Energy Institute, EVN AG, HyCentA Research GmbH, K1-MET GmbH, Vienna University of Technology, University of Natural Resources and Life Sciences, VERBUND, voestalpine Stahl GmbH, WIVA P&G	[38]
Pyrolysis of natural gas	2022-2027	Evaluation of different technologies for the pyrolysis of NG to produce H_2 without CO_2.			Leoben, MUL	RAG Austria, voestalpine Stahl GmBH, MUL Leoben, Primetals Technologies, Wien Energie	[38]

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
HCMA (Hydrogen and Carbon Management Austria)		A pilot system for researching sector coupling industrial processes towards climate-neutrality, including CO_2 capture and utilisation processes. The benefits of green hydrogen for a decarbonised industry are being investigated.	14 MW peak load photovoltaic cells 6 MW electrolyser (PEM) 2 fuel cell buses…		Linz, Voestalpine Stahl GmbH	Voestalpine Stahl GmbH, Verbund, Rohrdorfer Zement, Energie AG	[41]
UpHy I	2018-2022	Development of advanced analytical methods to detect all desired hydrogen quality parameters				OMV Downstream GmbH, WIVA P&G, VERBUND Solutions GmbH, Energieinstitut an der, Johannes Kepler Universität Linz, Chair of Energy Network, Technology of Montanuniversität Leoben, VF Services GmbH, HyCentA Research GmbH	[42], [43]
UpHy II	2021-2025	Concepts for upscaling scenarios of green H_2 production by electrolysis as well as the corresponding logistics for distribution will be developed	300 bar trailer refilling hub and a 350 bar refuelling infrastructure for busses and trucks			OMV Downstream GmbH, WIVA P&G, VERBUND Solutions GmbH, Energieinstitut an der, Johannes Kepler Universität Linz, Chair of Energy Network, Technology of Montanuniversität Leoben, VF Services GmbH, HyCentA Research GmbH	[42], [43]

Table 8. Low carbon projects foreseen in Sweden*

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
HYBRIT	**2016–2017:** Prefeasibility study with support from Swedish Energy Agency 4-year R&D project with support from Swedish Energy **2017** A joint venture company between SSAB, LKAB and Vattenfall **2018–2024:** **Feb 2018** Decision for pilot phase **2019–2021** Fossil-free pellets trial **2020–2024** Hydrogen-based reduction and smelting trials **2021/22–2024** Hydrogen storage **2025–2045:** **2025** * Transformation - BF to EAF at SSAB Oxelösund * HYBRIT demo plant **2026** SSAB fossil-free steel on market **2030–2040** Transformation - BFs to EAFs at SSAB Raahe & SSAB Luleå **2045** SSAB fossil-free	Experimental combustion oven using biofuels, H_2 etc., for the pelletizing process. DR (H_2) Pilot plant and industrial scale. Melting trials in a 10t batch EAF. H_2 storage facility for underground storage (H_2 is compressed to 250bar)	4.5 MW electrolyser (ALK) (2020) 339 MW electrolyser (ALK) (2025) 1,3 Mt DRI/y (by 2026) 2.7 Mt DRI/y (by 2030)	Since 2019: Melting trials in EAF (test of biocarbon and others)/ August 2020: DR pilot plant inaugurated/ Fall 2020 start of operation DR(NG) Spring 2021: First trials with green H_2 in the DR pilot plant May 2021: Start construction of a storage facility for green H2 July 2021: First steel produced using HYBRIT technology was rolled by SSAB in Oxelösund	Lülea/ Gällivare	SSAB, LKAB, VATTENFALL	[44], [45], [30], [46], [47]

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
H2 Green Steel (H2GS)	2024 (start of production)	100% DR(H_2)/EAF steelmaking using dedicated renewables	5 Mt steel tonnes of steel (before 2030) 1.5 GW electrolyser		Boden, Norrbotten	IMAS Foundation, Vargas Holding, Scania, InnoEnergy, Altor, Bilstein Group, SMS Group, Exor, Kingspan, FAM, Mercedes, Marcegaglia	[30], [48], [49]
Hofors rolling project	2022		17MW electrolyser (ALK)				[30]
	2019	Build a biogas plant to partly replace the coal used to heat BF			Höganäs AB	Cortus Energy, Höganäs AB	[47]

Table 9. Low carbon projects foreseen in Italy*

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
Dalmine Zero Emissions		Construction of an electrolyser and adapt the steelmaking process to use green H_2 instead of NG. It would significantly reduce CO_2 emissions related to EAF steel. The construction of a storage site for the H_2 might be included	20MW electrolyser		Bergamo, Tenaris' Dalmine steel mill in Italy	Tenaris, Edison, Snam	[50]
Sicilian Sustainable Steel	2024	Feasibility study. Electrolyser powered by Solar PV	7MW electrolyser				[30]

Table 10. Low carbon projects foreseen in the Netherlands*

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
Everest (Enhancing Value by Emissions Reuse and Emission Storage)	Implemented in 2027	Build an installation to capture CO_2 from process gases. The captured CO_2 is delivered to the Athos network.			IJmuiden, Tata Steel	TATA STEEL	[51]
ATHOS (Amsterdam-IJmuiden CO2 Transport Hub & Offshore Storage)	Network expected to be operational in 2026	Manage transport, reuse and storage of CO_2		2019: Feasibility study completed	North Sea Canal area	TATA STEEL, Gasunie, EBN, Port of Amsterdam	[51], [52]
	Announced in 2021	Switch to DR(H_2)/EAF. 2 Direct reduction plants are planned to be installed	Before 2030: 2,5 Mt/y DRI (DRI1) 2032 or 2037: 3,5 Mt/y DRI (DRI2)	September 2021: Announcement switch to green steel	IJmuiden, Tata Steel	TATA STEEL	[53]
Hermes project	Production in 2024	Develop the largest green hydrogen cluster in Europe. Investigate the feasibility of a water electrolysis installation to produce hydrogen and oxygen in the Tata Steel plant	100 MW electrolyser Production of 15,000 tH_2/y Production of O_2		Amsterdam metropolitan area, IJmuiden Works.	TATA STEEL, Nouryon, Port of Amsterdam	[51], [54]
Hisarna	2011- 2033 (full scale)	Full scale development of Hisarna process (direct reduced iron process for iron making in which iron ore is processed almost directly into liquid iron). The process does not require the manufacturing of pellets, sinter, or coke).		Since 2011: in development 2021: Start of demonstration scale project		TATA STEEL	[51], [54]
SeaH2Land	2030	Linking GW-scale electrolysis to the large industrial demand in the Dutch-Flemish North Sea Port cluster through an envisaged regional cross-border pipeline.	1GW electrolyser (by 2030)		North Sea	Ørsted, Yara, ArcelorMittal Dow Benelux, Zeeland Refinery, North Sea Port, Smart Delta Resources, Province of Zeeland, Province of Oost-Vlaanderen.	[30], [55]

Table 11. Low carbon projects foreseen in France*

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
Carbalyst (Steelanol)	2022 (start production)	Construct a Carbalyst plant for the carbon capture from the BF waste gas, and biologically converting it into ethanol to use as a biofuel or recycled carbon feedstock for the chemical industry.	Reduce its CO_2 emissions by 20% before 2030		Fos-sur-Mer	Arcelor-Mittal, Lanzatech	[56], [57]
IGAR (Injection of Gas Reductant in blast furnace)		Capture of waste CO_2 from the BF and convert it into syngas that can be reinjected into the BF in place of fossil fuels to reduce iron ore. Since the amount of coal and coke needed is reduced, this process helps to reduce CO_2 emissions. This technology can be further leveraged by injecting additional CO and H_2 from external clean energy sources, such as green H_2	Cutting CO_2 emissions by up to 20%		Dunkirk, France	Arcelor-Mittal	[25], [58]
3D – carbon capture	2023 (expected completion date)	Capture CO_2 off-gases for transport and storage. It will be linked to the development of CO_2 pipeline infrastructure, as well as deployment of CO_2 reuse technologies in blast furnaces.	Capture CO_2 off-gases at a rate of 0.5 t CO_2/h		Dunkirk, France	Arcelor-Mittal	[25]
	2025 (Commissioning)	DR/EAF plant. The project includes low carbon H_2 usage	2 Mt/y HM	March 2021: Air Liquide and ArcelorMittal signed a Memorandum of Understanding for the implementation of solutions to produce low-carbon steel in Dunkirk.	Dunkirk, France	Arcelor-Mittal, Air Liquide	[25]

Table 12. Low carbon projects foreseen in Belgium*

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
Torero	2018 - 2022 (reactor 1) & 2024 (reactor 2)	Construction of a large-scale demo plant to convert waste wood into bio-coal (by torrefaction), to replace fossil coal in the BF	Conversion of 120,000 tonnes of waste wood annually into bio-coal. Production of 80 000 t/y of bio coal	2018: Start of the project February 2021: start of plant construction	Ghent, Belgium	ArcelorMittal, TorrCoal, Renewi, Chalmers, Joanneum Research, University of Graz	[59], [60]
Steelanol (Carbalyst technology)	2022 (commissioning)	Construction of the first large-scale plant to capture carbon from the steel-making process and biologically convert it into bioethanol	80 million l/y ethanol	March 2021: Four bioreactors were delivered	Ghent, Belgium	LanzaTech, ArcelorMittal, Primetals, E4tech	[61], [62], [25]
CarbHFlex		Usage of microbes to produce acetone and isopropanol				Arcelor-Mittal	[25]

Table 13. Low carbon projects foreseen in Spain*

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
Sestao: zero carbon-emissions steel plant Gijon: new DRI and EAF	2025 (completion date)	Construction of a DR(H_2) plant + hybrid EAF in Gijon. The initiative involves the construction of large-scale solar farms	2,3 Mt/y DRI (Gijón) 1,6 Mt/y Steel (2025,Sestao)	July 2021: Memorandum of understanding signed with the Government of Spain that will see an investment of €1 billion	Arcelormittal, Gijon, Asturias	Arcelormittal	[30], [25]
		Injection of recovered H_2 and CH_4 containing gases from the coke ovens into the BF to reduce CO_2 emissions		Project announced in February 2021	Arcelormittal, Gijon, Asturias	Arcelormittal	[25],

Table 14. Low carbon projects foreseen in Greece*

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
Nemo Hydrogen Project	2025	Solar PV for electrolyser	100MW electrolyser				[30],
White Dragon	2022-2029	Replacement of the current use of lignite in Greece with extensive solar installations and 1.5 GW of solar oxide fuel cells, producing H_2, power, and heat. By 2029, the phase out of 2.1GW of lignite-fired capacity will be supported by the usage of renewable energy to produce green H_2, to decarbonize Greece's energy system. Heat will be fed into the existing district heating systems and transport excess hydrogen through existing international NG infrastructure.	250 tH_2/y (~8.5TWh thermal energy)		Western Macedonia, Greece	DEPA Commercial, Advent Technologies, Damco Energy (Copelouzos Group), PPC, DESFA, HELLENIC PETROLEUM, Motor Oil, Corinth Pipeworks, TAP, Terna Energy	[63], [64], [65], [66], [67]
Green HiPo		Manufacturing HT-PEM fuel cells for producing heat and power. Also involved the construction of a plant for producing innovative electrolytes and fuel cells			Western Macedonia, Greece		[64], [66],

Table 15. Low carbon projects foreseen in Finland*

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
	2030-2040	Convert the BF in Raahe to an EAF to eliminate most of the remaining CO_2 emissions.			Raahre	SSAB	[68],
FFS – Towards Fossil-free Steel		Explore different solutions and alternatives to produce fossil-free steel		Continuation of the 2020 Energy4HYBRIT prefeasibility project	Raahre	SSAB, Ovako, Fortum, Valmet, Nordkalk, Tapojärvi, Luxmet	[69],

Table 16. Low carbon projects foreseen in Poland*

Name project	Timeline	Description	Capacity	Status	Location	Project Partners	Lit.
		Usage of COG in the BF. Increase of NG consumption and reduction of the consumption of coke in the BF. Upgrade the tuyere elements to be able to additionally increase NG use		2020: increase NG consumption and reducing the consumption of coke	Dąbrowa Górnicza.	ArcelorMittal	[70],

* Overview based on literature research. Current status of developments not cross-checked with mentioned project partners.