European Steel with Hydrogen

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Abstract: The medium-term defossilisation of the steel industry is a basic prerequisite for achieving the European "Green Deal" aim of net zero emissions in 2050. The following analysis addresses the question of what regionally resolved, energy-related changes result from a 100% conversion of coke-based to hydrogen-based steel production in Europe. The main focus is on the additional hydrogen consumption arising from the transformation of Europe's steel industry. The analysis shows that the 100% switch of the steel industry from blast oxygen furnace (BOF) to direct reduction of iron (DRI) with subsequent smelting in an electric arc furnace (EAF) is accompanied by an increase in hydrogen consumption of 288 TWh. Comparable studies include significantly lower hydrogen consumption. The direct and indirect electrification (hydrogen) of the steel industry raised the European electricity consumption by about 510 TWh an increase of the European electricity consumption in 2018 (~2800 TWh) of about 18%. The regional analysis points out that especially in northwestern Europe the high additional hydrogen consumption of about 140 TWh meets an already partly existing hydrogen infrastructure in France, Belgium, the Netherlands and Germany. Accordingly, it can be assumed that the north-western part of Europe is a major driver of hydrogen consumption in Europe due to the local steel industry. Numerous previous research studies confirm that from a technical point of view DRI with EAF enables an almost climate-neutral steel industry.

1 Background and Motivation

The transformation of the steel industry forms the fundamental basis of a prospectively greenhouse gas neutral European industry [6]. Like no other industry in Europe, primary steel production uses into coal converted coke, which is currently needed in the BOF for the reduction of ferrite to iron. More than 99% of the final energy (376 TWh) used in European blast furnaces to produce 100 Mill. t. of primary steel in 2018 is due to CO_2-intensive coal and its derivatives [1], [7], [8]. Just under 72% of the energy consumption (total: 787 TWh) and over 80% of the fuel consumption (total: 673 TWh) of the overall iron and steel industry in Europe in 2018 is attributable to coal [1]. With an emission factor of 0.38 tCO_2/MWh [9], the European steel industry emits approximately 215 Mill. tCO_2 per year through the use of coal. For this reason, the medium-term defossilisation of the steel industry is a basic prerequisite for achieving the European "Green Deal" aim of net zero emissions in 2050 [10].

The defossilisation of the steel industry requires a timely, fundamental change in core processes based on new "breakthrough technologies" [11]. This could limit the extent of the alternative "Carbon Capture and Storage (CCS)" and the associated storage of large quantities of CO_2 to achieve the European climate goals. From today's technological point of view, the most feasible option for almost complete CO_2 abatement without CO_2 capture is hydrogen-based primary steel production (DRI with EAF) [2], [3], [4], [5], in which hydrogen is used instead of coke for the reduction of ferrite [12], [13], [14], [2], [15], [16], [17], [18], [19]. In order to process the direct reduced iron into crude steel, it is necessary to melt down and add small

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amounts of carbon in the EAF [14], [2], [19]. Due to the almost complete switch from BOF to DRI with EAF, considerable additional hydrogen consumption in Europe can be expected.

The subsequent analysis addresses the question of which regionally resolved, energetic changes would result from a 50 or 100% switch from coke to hydrogen-based steel production. The main focus is on the additional hydrogen consumption caused by the transformation of the steel industry. The research concludes with the evaluation of the energy-related results.

2 Current state of research

Due to the high absolute and specific energy consumption and the associated CO_2 intensity, industrial steel production is subject of numerous energy-related research activities.

The European steel industry is in the scope of techno-economic analyses in European energy and climate-policy scenarios [20], [21], [22], [23], [24], industrial European scenarios [25], [26], [27], [28], [29], sector-specific European technology paths [30] and sector-specific roadmaps [31], [32], [33]. Table 2-1 summarizes the criteria relevant to the research questions and identified current state of research.

Table 2-1: Overview of the relevant criteria and the identified publications within the research

	Publication	Steel industry					Regionalized resolution, prospective H_2 consumption of steel industry		
		Steel included in analysis	Focus steel industry	DRI with EAF	Production volume DRI with EAF in 2050	H_2 consumption according to DRI in 2050	Europe	Member States	Locations
1	[22]	x					x		
1	[24]	x					x		
1	[20], [21]	x		x	x		x		
1	[23]	x		x		x	x		
2	[25]	x		x		x	x		
2	[26]	x		x	x		x		
2	[27]	x		x			x		
2	[28]	x		x	x	x	x		
2	[29]	x		x	x		x		
3	[30]	x	x	x			x		
4	[33]	x	x	x			x		
4	[31]	x	x			x	x		
4	[32]	x					x		

[1]European energy and climate-policy scenarios, [2]European industrial scenarios, [3]sector-specific European technology pathways, [4] sector-specific European roadmaps

x: true; empty box: false

The balances of European energy and climate-policy scenarios [22], [24] include the steel industry, but do not provide detailed results for it due to the overall systemic focus. For example, [22] and [24] do not provide information on the prospective hydrogen consumption of the steel industry. In contrast, the browser-based visualization of [20] in [21] as well as [23] move the European steel industry increasingly in the focus. [21], however, does not contain any hydrogen consumption either, but does include the production volume and the specific energy carrier consumption per steel route at European and country level. In this context, [21] translates steel-specific hydrogen consumption directly into electricity equivalents. As a result, electricity consumption can no longer be clearly assigned to the hydrogen-based production process. [23] contains the hydrogen consumption of the DRI with EAF on the European level in 2050. The allocation of hydrogen consumption to production volume of individual processes and the total consumption of the European steel industry does not include [23]. [23] provides the hydrogen consumption, but is nevertheless limited to the European level resolution of the results [22], [24].

The industrial European scenarios [25], [26], [27], [29], [28] provide a highly heterogeneous level of detail. [26] and [27] include several process routes of the European steel industry, but do not identify their hydrogen consumption. [27] is limited to the description of process routes, whereas [26] balances the production volume of the DRI with EAF and the associated electricity consumption. As in [21], the electricity consumption cannot be clearly allocated to the respective production process in [26] either. This removes the option of determining the hydrogen consumption indirectly via power consumption in combination with a conversion factor. The studies [25], [29] and [28] provide in-depth techno-economic analyses of the European steel industry, including hydrogen consumption. [29] calculates the hydrogen consumption of the European steel industry in 2030. The analyses do not include the degree of switch to DRI with EAF [29]. [25] calculate the hydrogen consumption of the European steel industry in 2050, but do not allocate it to the respective production volume of the process routes. However, the figure without sufficient data labeling in [25] only allows an estimate of hydrogen consumption in the iron and steel industry based on the axis. [28] conducts a detailed process-specific analysis of the European steel industry. Accordingly, the hydrogen consumption can be assigned to the production volume per process route. Values for the European steel sites with high regional resolution (e.g. region-specific or site-specific) are not included in any of the European industrial scenarios analyzed [25], [26], [27], [29], [28].

The sector-specific European technology path in [30] includes non-energy-specific scenarios of the European steel industry with a time horizon up to 2030. Despite the research focus that differs from this publication, [30] is highly relevant with regard to the contained fundamentals of the respective steel routes.

The European sector-specific roadmaps [31], [32] and [33] focus explicitly on the European steel industry. The studies show in various scenarios how the steel industry develops up to 2050 from the perspective of the industry associations EUROFER [31], [33] and VDEh [32]. In the "Alternative Pathways" scenario, [31] reports hydrogen consumption for the European steel industry in 2050. However, [31] does not specify the production volume of individual process routes (e.g. DRI steel) in the path. [33] is the predecessor study of [31], which does not provide a higher level of resolution of the results. [32] focuses on CO_2 abatement options, energetic parameters are rarely included. None of the analyzed industry-specific Roadmaps contains values for the European steel sites with high regional resolution (e.g. regionally or site-specific) [31], [32], [33].

The literature review reveals that only few studies report the additional hydrogen consumption caused by the switch of the European steel industry to DRI with EAF [23], [25], [28], [31]. An allocation of the hydrogen consumption to the production volume of the DRI with EAF is only possible in [28]. Regionally high-resolution analyses of additional hydrogen consumption in the steel industry are not known to the authors. If regional analyses are conducted, they refer either to the steel sites [31], [33] or to the sites including production capacities or volumes [29] in Europe.

In addition to the similar studies according to our own research, other publications are highly relevant. For example, [34] compiles the national perspective of the hydrogen ramp-up, which reflects the hydrogen strategies of Europe and the European member states [35], [36], [37], [38], [39], [40], [41]. [34] thus provides the basis for the comparative analysis to validate and plausibilise the results. National publications such as [42] and [43] also contain relevant comparative values for the most important European steel-producing nation, Germany.

Specialist publications on the steel industry create the techno-economic basis for conducting scientific analyses [12], [13], [14], [2], [15], [3], [4], [17], [18], [19].

Thus, [12], [14] and [13], [18] determine the energy balance of the steel production of the DRI with EAF in theoretical models. The studies provide a solid technical overview of the relevant process routes in the steel industry.

In contrast, [2], [15] and [19] analyze steel routes on the basis of real data. [15] balances several steel production routes in terms of energy consumption and CO_2 emissions. The study provides the energy-specific consumption for individual process routes. However, the DRI with EAF uses natural gas instead of hydrogen in [15]. Accordingly, an almost complete CO_2 abatement is not achieved in [15]. [19] derives the importance of several steel routes from a European perspective using natural reinvestment cycles. As soon as an investment decision is made, the model selects the process route with the lowest CO_2 emissions per location. The analysis in [19] only contains the energetic differences of innovative production processes to the reference “BOF”. The main focus of [2] is on balancing the CO_2 emissions of steel processes [2]. [2] is highly relevant due to the associated complete energy balancing of the coke and hydrogen steel route, including the system boundaries.

[4] uses a global energy system and a scrap availability model to derive the importance of individual process routes for steel production from a global perspective. [4] confirms that a strong penetration of the DRI with EAF can be expected in the future, also from an economic perspective, depending on the CO_2 price. [3] uses a multi-criteria analysis (technology, social and political aspects, economy, safety and ecology) to underline the assessment of [4] that innovative steel production processes will have significantly higher preference values than the BOF route in 2050 [2].

[17] compares current alternatives for conventional steel production. One component of the analysis is DRI with EAF. The authors make an assessment regarding the marketability and technical parameters per process route.

3 Methodological Procedure

Figure 3-1 visualizes the methods used and illustrates the five-step procedure.

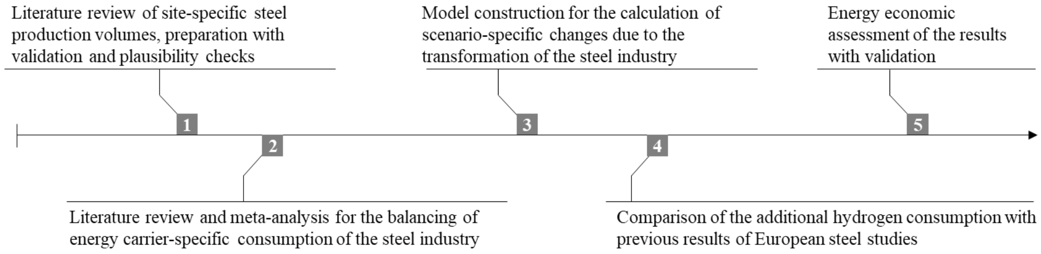

Figure 3-1: Methodology

Production volumes per primary steel site in Europe form the basis for the bottom-up data collection of regional energy carrier-specific consumption. The production volume for each location is determined by literature analysis based on the annual reports of European steel companies (Step 1). Data availability differs widely depending on the company. The company data is usually not calendar year-specific and does not adequately reflect the annuity applied in statistical data. Often companies with several steel sites aggregate relevant data sets in their final reports, which makes it difficult to assign data to specific locations. The lack of distinction between primary and secondary steel production in company data prevents process-specific analysis. In addition, some annual reports do not include site-specific production volumes. The challenges arising from the collection of site-specific data require further processing of the production volume.

Based on statistical country-specific data, the production volumes are prepared in a four-step process. The preparation process first defines a common base year for the analysis based on the timeliness and frequency of the data sets (sub-step 1). In the absence of on-site production volume in the company reports, the production capacities are used. If aggregated data are available for several sites, the procedure distributes the production volume or production capacities equally. Sub-step 2 finally allocates not site specific production volumes on the basis of site-specific production capacities in [44]. If European member states only include one primary steel plant, the company data can be validated directly on the basis of the statistical country-specific data and, if necessary, adopted [7], [8] (sub-step 3). In some member states, the researched site-specific production volume deviates by up to 46% from the officially published statistical data in [7], [8] (casu quo Italy). Remaining sites with production volumes deviating from the base year are updated by the preparation process, if possible, e.g. on the basis of the production capacities at the specific sites [44] in combination with statistical country data [7], [8] (sub-step 4). If the option of production volume adjustment is not available, the preparation process adopts the year-specific values for the base year.

In addition to the production volumes, specific consumption of each energy carrier of the BOF and DRI-Route must be collected in order to calculate the current and future absolute energy consumption bottom-up (2). The specific steel consumption data available in literature are heterogeneous. As the specific energy consumption has a significant influence on the result, a range is collected and validated and plausibility checked on the basis of current research projects. It is shown that the real data usually deviate significantly from the results of theoretical models. As there is a lack of specific consumption data in the literature on specific locations and energy carriers, the model applies the selected value equally to the European primary steel locations under investigation. This is based on the assumption that the European steel locations have a similar technological level and that energy consumption is at a similar level due to European-wide regulations.

The site-specific primary steel volumes in the status quo form the basis for determining the prospective production of European steel locations in 2050 (3). The required rate of change in production volume is calculated on the basis of the explicitly stated route-specific production volume in the EU reference scenario of, among others, the Potsdam Institute for Climate Impact Research, Imperial College London and TU Delft [21]. The total primary steel production in 2050 results from the aggregation over the different process routes of the scenario (BOF, DRI with EAF, HIsarna). The model constructed in this publication relates the rate of change between the base year and 2050 [21] to the site-specific production volumes by using their share in the aggregated European steel production. The procedure implies that neither new steel locations in Europe will be created nor existing ones abandoned.

The switch to hydrogen steel production and the associated site-specific results are calculated endogenously by the model. The model determines bottom-up site-specific and energy carrier-specific consumption of the steel locations in two scenarios. The scenarios include a 50% and 100% conversion of coke to hydrogen-based primary steel production in Europe. Finally, the results are compared with existing European studies with the same research focus.

4 Input data for modeling

Table 4-1 contains the researched and processed site-specific primary steel production volumes for the base year 2018 with the associated literature. The table also includes the primary steel production volumes in 2050 calculated in the model using the exogenous scenario [21].

Table 4-1: Analysed and calculated primary steel production per location

EU Member State	Individual Locations	Volume of primary steel produced in tons (t)			
		2018	Literature	2050	Literature
Austria	Donawitz	1 481 770	[45], [44], [7], [8]	1 120 014	Literature of the base year 2018 and own model calculations with the input from [21]
	Linz	4 694 075	[45], [44], [7], [8]	3 548 073	
Belgium	Ghent	5 450 000	[46]	4 119 448	
Czech Republic	Trinec	4 691 100	[47], [7], [8]	3 545 824	
Finland	Raahe	2 798 550	[48], [7], [8]	2 115 317	
France	Fos-sur-Mer	3 750 000	[46]	2 834 482	
	Dunkerque	6 850 000	[46]	5 177 654	
Germany	Bremen	3 300 000	[46]	2 494 344	
	Völklingen	2 782 000	[49]	2 102 808	
	Eisenhüttenstadt	2 150 000	[46]	1 625 103	
	Duisburg-Huckingen	4 575 650	[50], adopted from 2017	3 458 560	
	Duisburg-Beeckerwerth	6 000 000	[51]	4 535 172	

	Salzgitter	4 600 000	[52], [53]	3 476 965	
	Dillingen	2 334 000	[54]	1 764 182	
	Duisburg	1 120 000	[55]	846 565	
	Duisburg-Bruckhausen	6 000 000	[51]	4 535 172	
Hungary	Dunauijvaros	1 658 826	[56], [7], [8]	1 253 843	
Italy	Taranto	4 513 888	[45],[7], [8]	3 411 876	
Netherlands	Ijmuiden	6 813 000	[57], [7], [8]	5 149 688	
Poland	Krakow	1 995 775	[46], [44]	1 508 530	
	Dabrowa Gornicza	3 454 225	[46], [44]	2 610 918	
Romania	Galati	2 050 000	[46]	1 549 517	
Slovakia	Kosice	4 531 452	[58], [7], [8]	3 425 152	
Spain	Gijon	2 451 613	[46], [44]	1 853 081	
	Aviles	2 298 387	[46], [44]	1 737 263	
Sweden	Lulea	2 104 799	[48]	1 590 938	
	Oxeloesund	1 372 695	[48]	1 037 568	
United Kingdom	Port Talbot	3 785 000	[59], adopted from 2017	2 860 938	
	Scunthorpe	2 800 000	[60]	2 116 413	
Overall:		102 406 805	Rate of Change, 2018 to 2050 -24%	77 405 409	[21]

For the base year, the company-specific data on the steel volumes produced by the EU member states Spain, Poland and Austria are broken down by [44] based on the capacity per site. The company data for member states with only one primary steel site (Czech Republic, Finland, Hungary, Italy, the Netherlands and Slovakia) deviate too much from the statistical values (more than 10%). Accordingly, the preparation process takes the production volume for the countries listed per location from the statistics [7], [8]. In the remaining European member states with only one primary steel location, steel production deviates by less than 9% from the site-specific production volume. According to the EU Reference Scenario in [21], the prospective total steel production will decrease by 24% between 2018 and 2050 over all European steel locations.

Table 4-2 compares the researched company data of European steel sites with the statistics [7], [8] and the specially calculated scenarios based on [21].

Table 4-2: Staticstical and searched data as well as scenario results on steel production in Europe

Process route	Literature	Production volume (t) and deviation (%)		
		2018	Deviation statistical data in (%) 2018	2050
Primary steel (e.g. BOF, DRI with EAF, Hlsarna process)	[21]	104 146 000	+ 5.2	78 720 000
	Individual Locations	102 406 805	+ 3.5	77 405 409[1]
	[7], [8][3]	98 967 342	BV[2]	-
Secondary steel	[21]	72 170 000	+ 5.5	74 170 000
	[7], [8][3]	68 402 658	BV[2]	-

[1]Calculation on the basis of [21]; [2]Basis value; [3]Statistical Data

Table 4-2 shows that the investigated company data deviates only 3.5% and the scenario results only 5.2% from the statistics [7], [8]. A relevant influencing factor for the estimation of plausible production volumes in metallurgical processes is the respective secondary share. Table 4-4 describes the secondary share of the European steel industry in 2018 of the statistics [7], [8] and the scenario [21]. In 2050, the secondary share in the scenario increases to about 48%, mainly due to the declining primary steel production in Europe [21].

Table 4-3: Share of secondary steel in the statistics and in the scenario

	Literature	2018	2050
Share of secondary steel in %	[21]	40.93	48.51
	[7], [8][3]	40.87	-

In the literature, the energy carrier-specific consumption of BOF and DRI based steel production exhibits a high degree of heterogeneity. This is due in part to different system boundaries in the steel industry. In addition, there are significant differences depending on whether the studies are based on a theoretical model or on real data. Research based on real data usually indicates significantly higher energy consumption. Accordingly, care must be taken when choosing the specific energy consumption and a complex validation is necessary. The researched and selected specific consumptions of BOF and DRI with EAF steel production and the corresponding delimitation of the balance area in Table 4-4 contain real data based on [2]. The negative specific electricity consumption of the BOF results from the difference between internal electricity consumption and internal electricity generation in top gas power plants, which is particularly common in integrated steel plants.

Table 4-4: Specific energy consumption

Process route	Literature	Included	Excluded	Specific energy consumption in MWh/t	
				spec. electrictiy consumption	spec. fuel consumption
BOF	[2]	coke oven, sinter plant, blast furnace, top gas power plant (utilization factor 0,5)	Mining, transport, ore processing, further processes such as casting	-0.139	5.325
DRI with EAF		Direct reduced iron & Electric arc furnace		0.726	4.001

Theoretical analyses such as [13] and [61] prove a fuel consumption of up to 1.5 MWh/t lower for DRI with EAF. A European steel production of more than 100 Mill. t. per year would result in an energy difference of ~172 TWh in Europe.

Table 4-5 summarizes the energy-specific distribution of the process routes, which was researched and selected for the analyses.

Table 4-5: Distribution of consumption according to energy carrier

Production Process	Literature	Share of energy carrier (dimensionless (dl))			
		Natural Gas	Coal	Biomass	Hydrogen
BOF	[2]	0.012	0.988	-	-
DRI & EAF		0.44	0.07	-	0.49
DRI & EAF, transfer of the heat supply to hydrogen[1]	based on [2]	-	-	0.07	0.93

[1]Selected for the analysis

According to [12] the analyses assume that the heat supply in the DRI with EAF can also be provided using hydrogen instead of natural gas. Accordingly, the model substitutes the CO_2 emitting natural gas with potentially climate-neutral hydrogen by 2050. The model obtains the small amounts of carbon required for melting in the electric arc furnace [14], [2], [19] from highly processed biomass. The basic energy values of the two analyzed process routes in the steel industry are visualized in Figure 4-1.

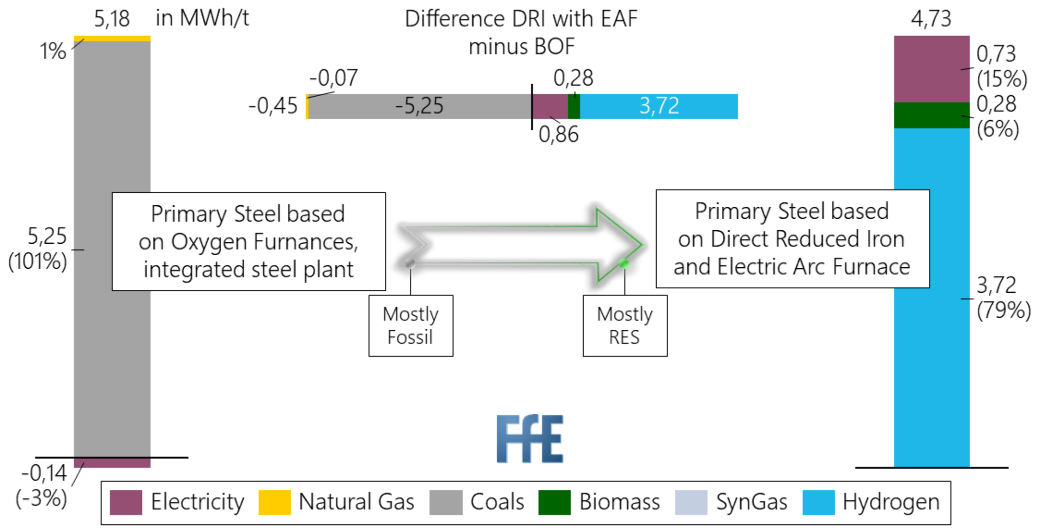

Figure 4-1: Energy base values blast furnace steel (left) and DRI with EAF (right)

5 Results and Discussion

Figure 5-1 shows the regionally resolved primary steel production of Europe in 2018. As the analysis examines the shift from BOF to DRI with EAF and the resulting prospective hydrogen consumption, the primary steel plant in Hamburg (Germany), which is already equipped with a direct reduction, is excluded. The Hamburg plant still uses natural gas instead of hydrogen in the direct reduction facilities. The production capacity is around 6 000 kt [62].

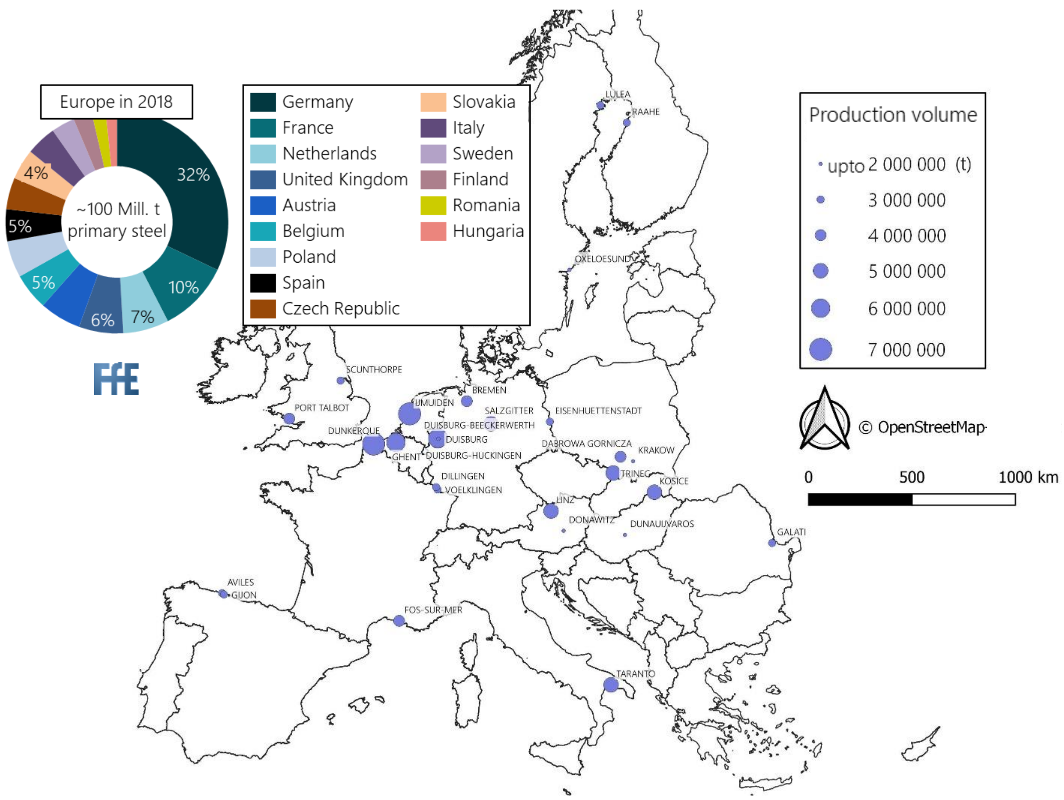

Figure 5-1: Primary steel production in Europe in 2018

The regional resolution of the European primary steel industry illustrates that the northwest of Europe in particular produces substantial steel volumes in France (Dunkerque), the Netherlands (Ijumuiden), Belgium (Ghent) and Germany (eight locations). In total, the region produces about 50 Mill. t. steel in 2018, which corresponds to a share of ~48% of the current primary steel production in Europe.

Figure 5-2 contains the calculated production volume of the European steel sites in 2050 based on [21]. Small (blue) and large (red) production sites in Europe are highlighted. Due to the declining primary steel production (-24%) reported in [21] and used in this study, the production volume across all sites will decrease equally compared to the base year 2018.

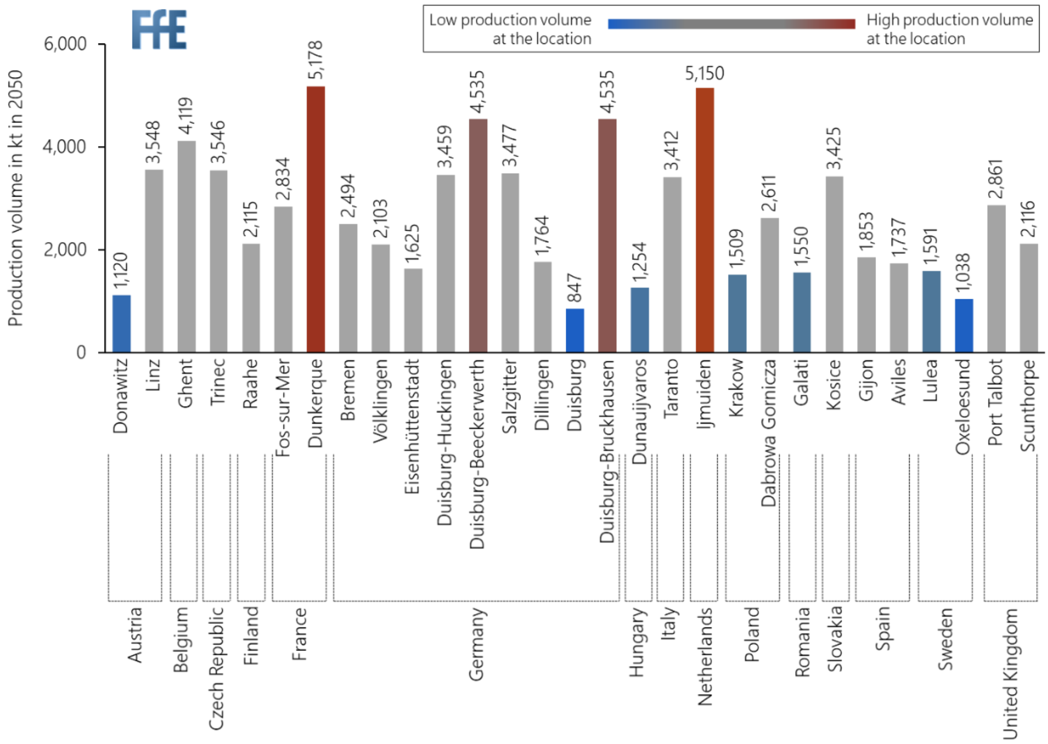

Figure 5-2: Site-specific primary steel production based on individual site-specific research and the EU reference scenario from [21]

The regionally resolved hydrogen consumption calculated in the model on the basis of the production volumes at the specific locations and the specific energy consumption is visualized in Figure 5-3. Figure 5-3 shows that the hydrogen consumption will increase by about 288 TWh in 2050 in the European Union if steel production is completely switched to DRI with EAF. This corresponds to about 86% (339 TWh) of the current hydrogen consumption of the European Union (2018) [23]. However, the electrolysis capacity of 40 GW (333 TWh, 8 325 full-load hours) planned by the EU in 2030 could already more than cover hydrogen consumption if steel production is completely converted to DRI with EAF [35]. Another option is the import of hydrogen from countries close to the EU such as Russia and the Ukraine. The combined goals of the two countries target a green hydrogen production of about 200 TWh per year from 2030, and both show willingness to export their production [34].

Compared to the EU-wide average of an 86% increase in hydrogen consumption, Germany in particular will require high amounts of hydrogen when the steel industry switches to DRI with EAF. From the 288 TWh of the additional hydrogen consumption, just under 32% (92 TWh) is attributable to Germany. In comparison to the current use of hydrogen mainly as feedstock in German chemical plants and refineries, amounting to 55 TWh [36], hydrogen consumption will increase by about 167% due to the transformation of the steel industry. This means that the steel industry alone would account for about 38% of the hydrogen consumption forecast in the national hydrogen strategy in 2050 (~245 TWh, forecast consumption between 110 and 380 TWh) [36]. This would require an electrolysis capacity of about 23 GW in Germany (4 000 full load hours). This corresponds to about 82% of the minimum electrolysis capacity of 28 GW in 2050 specified in the German hydrogen strategy. However, since it can also be assumed that significant hydrogen imports via prospective hydrogen pipelines within Europe are possible [63], the minimum scenario of the national hydrogen strategy does not seem to underestimate the required electrolysis capacity.

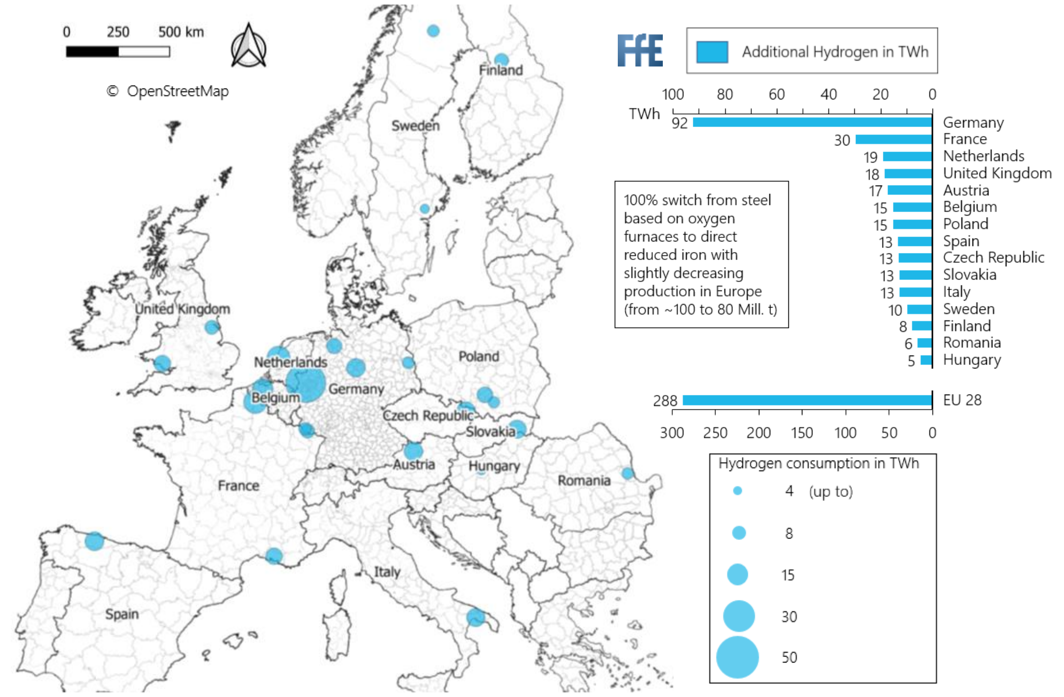

Figure 5-3: Regionally resolved hydrogen consumption of the steel industry in Europe with 100% switch of BOF steel production to DRI with EAF, centralised per district at NUTS-3 level

This evaluation also excludes the primary steel site in Hamburg (Germany) with its existing natural gas-based direct reduction. With a specific fuel consumption of about 4 MWh/t and a steel production of about 6 000 kt, an additional hydrogen consumption of ~2.4 TWh would result in Hamburg [2], [62]. Furthermore, the low capacity utilization of the Italian steel site in Taranto creates high uncertainties regarding the calculated hydrogen consumption in Italy and thus in Europe. If the Italian steel site were fully utilized with a production capacity of 9.5 Mill. t, increasing from the current production volume of only 4.5 Mill. t, Italy's hydrogen consumption calculated in the scenario would more than double. European hydrogen consumption would thus increase by more than 13 TWh.

The regionally resolved production volumes in Figure 5-1 already suggest that the European Northwest (France, Belgium, the Netherlands, and Germany) would prospectively require significant amounts of hydrogen. Figure 5-4 confirms the initial assumption.

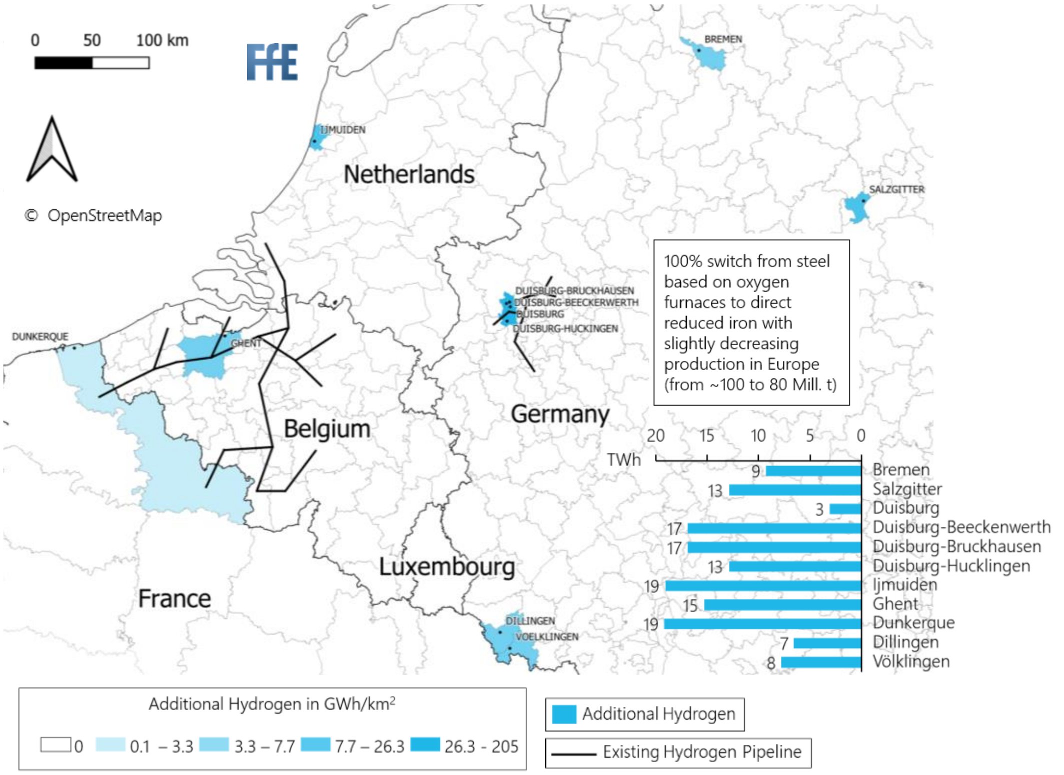

Figure 5-4: Regionally resolved hydrogen consumption of the steel industry in Europe's northwestern with 100% switch of steel production to DRI with

The North-West European steel industry requires about 140 TWh for the 100% switch of the steel industry to DRI with EAF, or almost half of the hydrogen consumption of the European steel industry. The first hydrogen transport grids are already in place to transport the prospective hydrogen consumption in the region. Belgium, the Netherlands and France in particular are already connected via a hydrogen pipeline. The connection of German hydrogen infrastructure in the German "Ruhrgebiet" could strengthen the cross-border exchange. A connection of Duisburg would mean an additional transport volume of about 50 TWh hydrogen in the 100% scenario.

The switch of BOF steel production to DRI with EAF is accompanied by other energy-related changes in addition to hydrogen, as described in Figure 5-5.

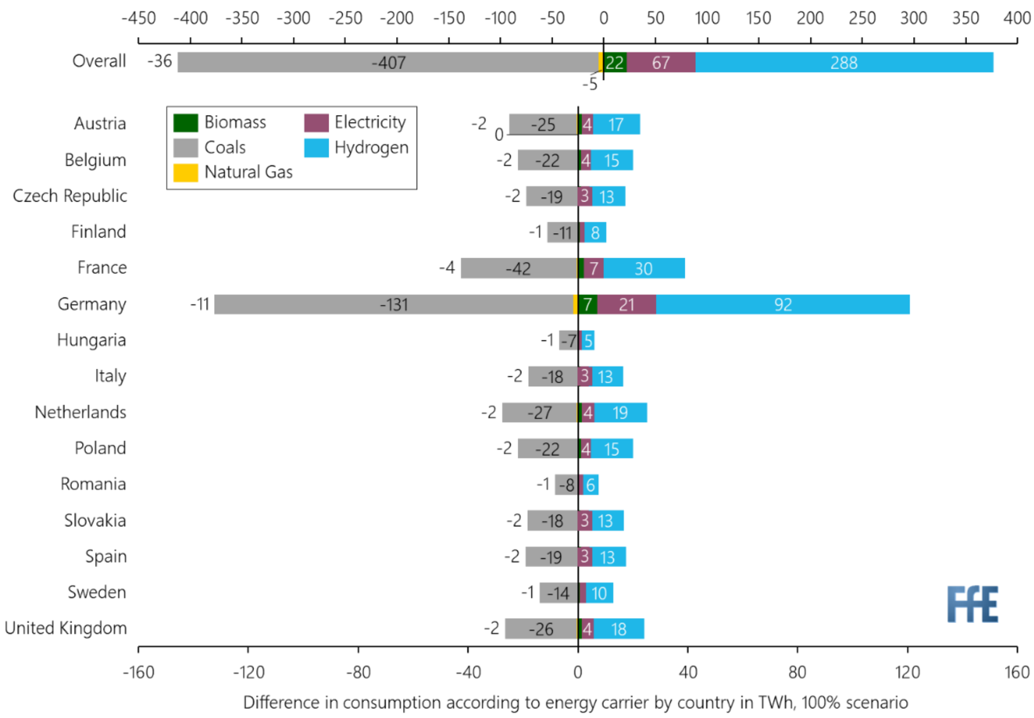

Figure 5-5: Difference in energy consumption due to 100% switch from BOF to DRI & EAF primary steel in 2050

The lower specific energy consumption of the DRI with EAF compared to BOF steel is associated with slight efficiency gains of 9% and thus a decrease in energy consumption of about 36 TWh. [28] estimates the efficiency improvements due to the transformation of the steel industry to be even higher at 19%. However, in [28] the steel industry will be switched 50% each to DRI with EAF and to plasma steel.

Due to the process change in the steel industry, not only the hydrogen consumption but also the direct electricity consumption (67 TWh) increases significantly, and to a lesser extent the biomass consumption as well (see Figure 5-5). In the scenario, the increase in electricity is due to the additional electricity of DRI with EAF steel production. Since, in contrast to BOF, DRI with EAF no longer produces top gas when reducing ferrite with coke, there is no longer any need for electricity generation in top gas power plants. With an electricity-based generation of hydrogen via water electrolysis and an assumed conversion and supply efficiency of 65% [64], the calculated hydrogen consumption of 288 TWh results in an additional electricity demand of about 443 TWh. In total, the direct and indirect electrification (hydrogen) of the steel industry results in an additional electricity consumption of about 510 TWh in Europe. This corresponds to an increase of about 50% in the electricity consumption of the European industry in 2017 (1035 TWh, [1]).

In Germany, however, the final energy consumption of about 228 TWh in 2017 would increase by more than 70% due to direct (21 TWh) and indirect electrification (142 TWh) of the steel industry [65]. Germany's total final energy consumption of about 500 TWh in 2019 [66] would increase by about 33%. To cover the additional electricity consumption in Germany, about 13 040 wind turbines with a capacity of 5 MW (2 500 full load hours) would have to be added. The number of plants would therefore increase by about 45% (29 200 wind turbines in 2018) [67]. In 2018, only 743 wind turbines were added in Germany, and in 2019 only 325 with an average capacity of about 3.2 MW [67].

In total, about 407 TWh of coal and 5 TWh of natural gas can be substituted by potentially climate-neutral energy carriers in Europe. In particular, coal consumption in Germany is decreasing significantly due to the transformation of the steel industry. A decrease in coal consumption by 131 TWh represents a decrease of almost 21% in the total primary energy consumption of hard coal and lignite in Germany (base year: 2019) [66].

Compared to the 288 TWh determined in this paper, similar studies show lower hydrogen consumption of between 80 TWh [25] and 246 TWh for the European steel industry in 2050 [28]. The hydrogen consumption depends largely on the extent of the switch to the DRI with EAF route and the energy-specific data. Likewise, the chosen form of providing high-temperature heat in the steel industry has a significant influence on hydrogen use. The heat supply can be carried out with hydrogen [12] as well as with fossil energy carriers such as natural gas [29], [2] and comprises about 44% of the energy consumption of the steel industry. Table 5-1 provides an overview of the steel-specific hydrogen consumption of comparable studies in 2050.

Table 5-1: Comparison of the results with further scenarios

Study	Production Volume DRI mit EAF in Mill. t	Hydrogen Consumption, Europe 2050, TWh
[23]	Not specified	140
[25], 4b Mix95 Scenario	Not specified	80-95 (estimated from figure)
[28], Scenario GHG-neutral EU2050	95 (50% plasma steel and 50 % direct reduction of iron ore with EAF)	246
[31]	Not specified	213
Own Results	77	288

Besides the complete switch to DRI with EAF in the steel industry, the model also calculates a scenario with a 50% process change. Inherent in the scenario is the option that a moderate level of climate ambition in Europe will emerge as a result of national independent initiatives. Based on linear calculations, European hydrogen consumption would be halved from 288 TWh to around 144 TWh. If, on the other hand, strong global climate protection with internationally uniformly high CO_2 prices is assumed, the production volume in efficient and thus climate-friendly, innovative steel facilities in Europe could multiply due to the expected worldwide increase in steel demand. Assuming a high level of climate protection with a complete switch to DRI with EAF and a doubling of European steel production (~200 Mill. t. of primary steel), European hydrogen consumption will also double in 2050 (~576 TWh). All scenarios assume that sufficient hydrogen is available for the steel industry.

6 Conclusion

The regionally resolved analysis of the European steel industry shows that the complete switch (100% scenario) of steel production to DRI with EAF will require an additional hydrogen consumption of about 288 TWh in 2050. Inherent to the 100% scenario is a 24% decrease in European primary steel production. Comparable studies show a significantly lower hydrogen consumption. The direct and indirect electrification of the steel industry will increase the European electricity consumption by about 510 TWh, an increase inform the 2018 level (~2800 TWh) of about 18% [1]. If the additional electricity consumption in Europe is to be served by renewable electricity, RES will need to be expanded to keep pace with the transformation of steel production. In total, about 407 TWh of coal and 5 TWh of natural gas can be substituted by potentially climate-neutral energy carriers in Europe. In Northwest Europe, the high additional hydrogen consumption of about 140 TWh meets with an already partially existing hydrogen infrastructure in France, Belgium, the Netherlands and Germany. Accordingly, it can be assumed that the north-western part of Europe will be a major driver of hydrogen consumption in Europe in the middle and long term due to the local steel industry. A comparison of the results with national hydrogen strategies is only possible to a limited extent, as the strategies mainly contain qualitative rather than quantitative insights.

The transformation of the steel industry has a particular impact on Germany as a steel-producing nation. The analysis calculates an additional hydrogen consumption of 92 TWh in Germany in 2050 (~30 Mill. t.) if the transformation to DRI with EAF is entirely completed. The hydrogen consumption is strongly dependent on how the future heat demand of the steel industry is provided. For example, [43] assumes that the heat share of the DRI steel of about 44% will be covered by natural gas. This reduces hydrogen consumption to about 46 TWh for the production of 23 Mill. t primary steel in [43]. For a climate-neutral steel industry it makes sense with regard to the conversion losses to use hydrogen instead of synthetic hydrocarbons to substitute natural gas.

Despite detailed analyses, this study still has limitations. For example, the analysis neglects the increase in energy efficiency in both steel routes. Furthermore, a detailed analysis of scrap availability is missing, which influences the conversion to DRI with EAF. In this respect, the analysis relies on the primary steel production volumes from [21] provided in the exogenous scenario. Furthermore, the evaluations exclusively analyze the effects of a complete conversion of the steel industry to DRI with EAF. Other processes such as plasma steel or the smelting reduction in the HIsarna process are neglected in the analysis. Accordingly, the additional research required as a result of the limitations is primarily based on a holistic view of the steel industry and a modeling of all process routes, taking into account efficiency increases and interactions, in order to derive the hydrogen consumption.

As a result of the European steel industry's extensive conversion to DRI with EAF, the prospective hydrogen consumption will increase significantly. With the National and European hydrogen strategies, first steps have already been taken to ensure the ramp-up of a European hydrogen economy [35], [36], [37], [38], [39], [40], [41]. The supply of hydrogen represents a challenge that the whole of Europe will have to address in the future. Numerous previous research studies [2], [3], [4], [5] confirm that from a technical point of view DRI with EAF makes a climate-neutral steel industry possible. The practical implementation is also imminent [29]: Steel companies in Sweden (1x), Germany (3x), Romania (1x) and Italy (1x) are either already planning DRI pilot or demonstration plants or are preparing concrete strategies to produce DRI steel on an industrial scale before 2030 [29].

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