InSGeP

Investigations of Slags from Next Generation Steel Making Processes

Deliverable 2.1

Data about future steel production figures and corresponding slag production

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Abstract

New process technologies and next generation iron and steelmaking methods are being developed to decarbonize the European steel sector. The majority of steel will be made by means of electric arc furnaces (EAF) or via the route of electrical melters coupled e.g., with a basic oxygen furnace (BOF) using a greater amount of pre-reduced iron in the burden. This means that finding appropriate solutions for the slag utilization that results from these processes is inevitable, as slag from the blast furnace (BF) – BOF route, which is currently used by a variety of industries (such as cement and road construction), needs to be replaced.

Starting with current steel production numbers, the deliverable describes steel industry trends and their implications. In recent years, Europe has placed great emphasis on sustainable and environmentally friendly steel production, with efforts being made to minimize carbon emissions (including transition to low-carbon energy sources), enhance circular economy practices, increase energy efficiency, and explore alternative technologies as well as to digitize and increase the usage of machine learning and artificial intelligence.

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AI	artificial intelligence
BF	blast furnace
BOF	basic oxygen furnace
CIC	Commonwealth of Independent States
DR	direct reduction
DRI	direct reduced iron
EAF	electric arc furnace
EU	European Union
HBI	hot briquetted iron
HPSR	hydrogen plasma smelting reduction
KOBM	Klöckner oxygen blown Maxhütte
KPI	key performance indicator
TRL	technology readiness level

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1 Introduction

Next generation iron and steelmaking processes to decrease CO_2 by using direct reduced iron (DRI) with varying reduction degrees, hot briquetted iron (HBI), hydrogen plasma smelting reduction (HPSR) or by operating electrical smelters for low-grade ores will result in an increase of electric arc furnace (EAF) slag and other slags with different properties. This requires the understanding of the possibility to valorize future slags in the present value chain and define innovative applications to assure a smooth transition process without disruption to the steel industry as well as other sectors (such as road construction or cement) who currently rely on slag as raw material for their processes. To understand and move forward the transition of the steel industry, InSGeP project is investigating slags resulting from next generation steelmaking in Europe. The project relies on the limited amount of currently produced slags from next generation steel production in Europe and abroad as well as on laboratory, pilot scale and industrial scale tests that will be performed based on the needs of the involved partners.

The state-of-the-art process routes for steel production are, on the one hand the combination of blast furnace (BF) and basic oxygen furnace (BOF) and on the other hand, the EAF, using scrap or coupled with a direct reduction (DR) process. In response to the directive to decarbonize the European steel industry, next generation iron and steelmaking routes are being implemented, and new process technologies are being developed to substantially decrease CO_2 emissions.

Deliverable 2.1 summarizes the expected future steel production developments and the corresponding slag quantities available, thereby focusing on trends within the steel industry, considering current production figures and by evaluating ongoing activities.

2 Current steel production

Steel manufacturing is an important aspect of Europe’s industrial environment, contributing significantly to the economic development. The European steel sector has a turnover of around €130 billion, with more than 500 manufacturing facilities throughout 22 European Union (EU) member states [1]. This production capacity supports a wide range of industries, from automotive manufacturing to construction and infrastructure development [2, 3]. The EU's crude steel production by nation for the year 2022 is depicted in the following figure (Figure 1). Germany is Europe's largest steel producer, accounting for 27% of total production. Further major European steel producers are Italy (15.8%), France (9%), Spain (8.4%), Austria (5.5%), Poland (5.4%) and Belgium (5.2%) [1].

	Country	Steel production in ‘000,000 metric tons	% shares
1	Germany	36,849	27.0
2	Italy	21,599	15.8
3	France	12,234	9.0
4	Spain	11,464	8.4
5	Austria	7,512	5.5
6	Poland	7,407	5.4
7	Belgium	7,030	5.2
8	Netherlands	6,143	4.5
9	Sweden	4,382	3.2
10	Czech Republic	4,262	3.1
11	Slovakia	3,872	2.8
12	Finland	3,538	2.6
13	Romania	2,625	1.9
14	Luxembourg	1,875	1.4
15	Others	1,855	1.4
16	Greece	1,543	1.1
17	Hungary	857	0.6
18	Slovenia	623	0.5
19	Bulgaria	482	0.4
20	Croatia	169	0.1
	EU 27	**136,321**	**100**

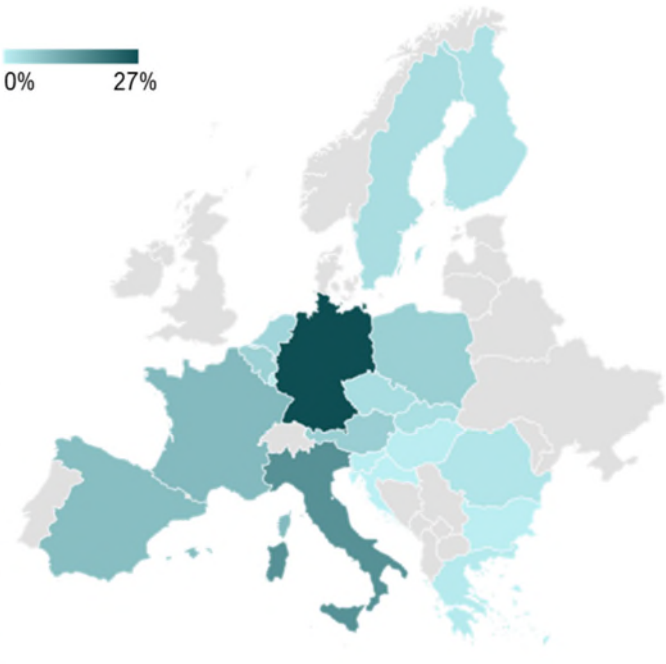

Figure 1: Crude steel production in the European Union (2022, based on [1])

Global steel output reached a total of approximately 1.9 billion tons in 2022 [4]. With 136 million tons of steel, the EU ranked as the world's second-largest producer of steel (7.2%), behind Asia (including China, India and Japan) whose output in 2022 accounts for around 73.9% of worldwide production [1]. Over the past 20 years, the amount of steel produced worldwide has increased, whereas in Europe, production has remained relatively stable [5, 6, 7].

[1] EUROFER: European Steel in Figures 2023.
[2] European Commission: Commission staff working document: Towards competitive and clean European steel, 2021.
[3] Annual Single Market Report 2021, Annex III.
[4] World Steel Association: World Steel in Figures 2023, 2023.
[5] World Steel Association: Steel Statistical Yearbook 2010, 2010.
[6] World Steel Association: Steel Statistical Yearbook 2016, 2016.
[7] World Steel Association: Steel Statistical Yearbook 2021: A cross-section of steel industry statistics 2011 - 2020, 2021.

The EU currently imports roughly 48 million tons of steel annually (excluding intra-regional trade), mainly from non-EU European countries, CIS and Asian countries and it exports 26 million tons mainly to non-EU European countries and North America [4].

The steel production process includes the preparation of raw materials, iron making, steelmaking, secondary metallurgy and continuous casting. The figure below (Figure 2) summarizes the crude steel output in the EU from 2013 to 2022, classified by production route. Two different production routes can be distinguished: the primary route, where steel is produced from iron ore, and the secondary route, where steel is produced from scrap melting. The primary route comprises the integrated route consisting of BF and BOF (BF-BOF), the smelting reduction route and BOF and the DR-EAF route consisting of a DR plant and an EAF. In contrast, the secondary steelmaking route produces crude steel by recycling steel scrap in the EAF.

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023 %shares
Basic oxygen furnace and other	90,191	92,946	91,526	91,489	93,928	91,937	86,655	74,189	86,261	77,310	56.7%
Electric	64,126	64,119	63,603	62,809	66,941	68,129	63,589	58,018	66,521	59,012	43.3%
Total crude steel	**154,318**	**157,065**	**155,129**	**154,298**	**160,869**	**160,066**	**150,244**	**132,217**	**152,782**	**136,321**	**100%**

in '000,000 metric tons

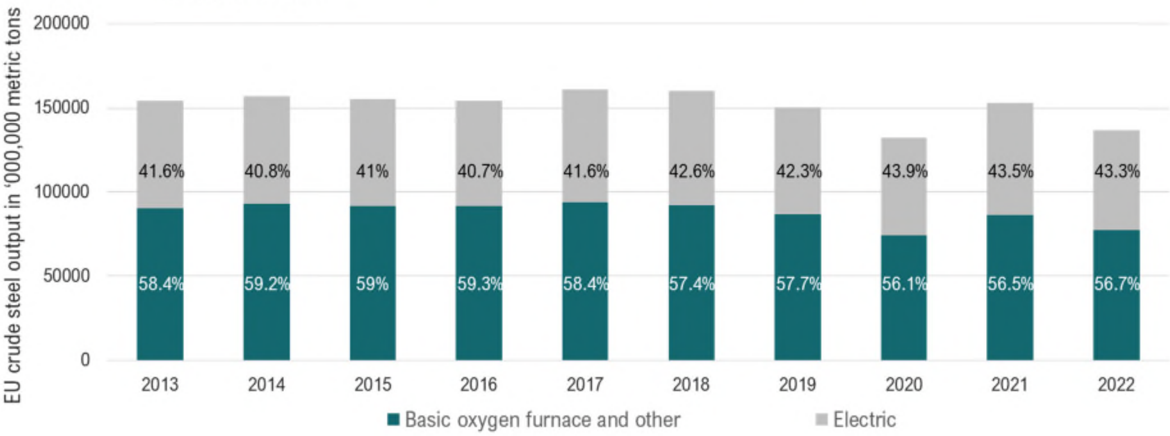

Figure 2: Crude steel production by production route between 2013 und 2022 (based on [1])

In 2022, the integrated route dominated the European steel production representing 56.7% of the crude steel production in the EU27, while the scrap based EAF route accounted for 43.3% [1]. Although there are regional differences, the share of crude steel production worldwide is higher compared to EU values with 71.5% for the BF-BOF route, 28.2% for the EAF route and 0.4% for other processes [4].

2.1 Blast furnace – basic oxygen furnace steel production route

The BF produces pig iron (hot metal), which is then refined and converted into crude steel in the BOF. These processes are usually complemented by secondary steelmaking processes for further refining and adjusting the steel properties. During iron and steelmaking, the generation and management of slag are integral components. In Europe, there are about 27 steel production facilities equipped with one or more BFs and / or BOFs [8].

The BF process generates BF slag during the production of hot metal by thermo-chemical reduction, and this process generates between 150 and 347 kg (249 kg on average) of BF slag for every ton of hot

[8] EUROFER: Where is steel made in Europe?, Online: www.eurofer.eu/about-steel/learn-about-steel/where-is-steel-made-in-europe (accessed on 01 February 2024).

metal [9, 10, 11]. The slag consists of impurities from the iron ore and combines with the fluxing agent, typically limestone, added to the furnace. The temperature of the BF slag at tapping is around 1500 °C. BF slag is typically granulated, or tapped into slag pits. Pelleting is an additional option, although it's not as common nowadays. Slag granules or pellets are often sold to the cement industry. However, pit slag can also be utilized in road construction [11, 12].

In the last stage of the BOF process, the crude steel and slag are tapped into separate ladles or pots at temperatures usually about 1600 °C. The slag is subsequently transferred into ground bays or pits, where it cools down. Various processes, like weathering, crushing, and / or screening, are applied to the crystalline slag to establish the necessary technical qualities for a particular usage. For every ton of crude steel, this process generates between 85 and 165 kg (125 kg on average) of BOF slag [9, 10, 11].

2.2 Electric arc furnace steelmaking

In the EAF process, steel scrap with the addition of fluxes and, depending on quality requirements, smaller quantities of solid or liquid sponge iron and pig iron, are heated to a liquid state by means of an electric current. Europe currently has 148 EAFs [8,13].

The utilized scrap derives from three distinct sources:

- Post-consumer scrap: This includes recovered metal from obsolete industrial structures (e.g., old machinery, railway and naval materials, discarded vehicles, and household appliances)
- Pre-consumer scrap: Generated within industries utilizing steel in their manufacturing processes, this comprises new scrap of varying grades
- Internal recoveries: Scrap produced within the own operations, spanning the steelmaking process within their facilities

Pre-consumer scrap generally has a cleaner chemical composition and exhibits less variability compared to post-consumer scrap. However, its utilization is restricted due to the higher cost associated with the production of superior steel qualities. Effectively managed internal recoveries can maintain a consistent chemical composition, leading to substantial savings on ferroalloys added during secondary metallurgy. It is important to note that it is also possible that some scrap grades originate from two different sources and are blended at the scrap yard before being charged into the furnace.

In addition, it is necessary to distinguish that while unalloyed steel scrap is used as the feedstock for carbon steel production, low-alloy or high-alloy steel scrap is used for the production of stainless / high-alloy steel (and optionally other metals (alloys) together with the fluxes to give the crude steel the desired chemical composition) [9].

The EAF slag is tapped at roughly 1600 °C and subsequently slowly air-cool, resulting in crystalline slag. The generated slag is a robust and compact, non-porous aggregate. Furthermore, it is cubic in shape, has good resistance to polishing, and has an affinity for bitumen [9]. Therefore, EAF slag is a

[9] EUROSLAG, Online, Online: www.euroslag.com (accessed on 31 January 2024).
[10] Rieger J., Colla V., Matino I. et al: Residue Valorization in the Iron and Steel Industries: Sustainable Solutions for a Cleaner and More Competitive Future Europe; In: Metals 2021, 11, 1202, 2021.
[11] Joint Research Centre, Institute for Prospective Technological Studies Remus R., Roudier S., Delgado Sancho L. et al.: Best Available Techniques (BAT) Reference Document for Iron and Steel Production. 2013.
[12] For more information on the fields of application and legal regulations, see D2.3.
[13] Lopez G., Galimova T., Fasihi M. et al.: Towards defossilised steel: Supply chain options for a green European steel industry, in: Energy, Volume 273, 2023.

suitable aggregate for asphalt surface material and road surface treatments [9]. For every ton of crude steel, this process generates between 60 and 270 kg (165 kg on average) of EAF slag [9, 10, 11].

3 Transformation of iron and steelmaking

In recent years, there has been a growing emphasis on sustainable and environmentally friendly steel production in Europe and various efforts to reduce carbon emissions, increase energy efficiency, and explore alternative technologies are underway. The following aspects provide a rough overview of current trends or developments within the steel industry:

- Carbon-neutral steel production including transition to low-carbon energy sources;
- Circular economy practices;
- Increased energy efficiency and
- Digitization and increased usage of machine learning and artificial intelligence (AI).

Since the deliverable addresses trends in the steel industry, advancements like digitalization, energy optimization, and artificial intelligence are included for completeness's sake. However, since the project's focus is on the slag of next generation steelmaking, they won't be described in greater detail.

3.1 Carbon-neutral steel production including transition to low-carbon energy sources

The steel industry is a significant contributor to global CO_2 emissions due to the energy-intensive nature of its production processes, primarily in the form of carbon dioxide released during the combustion of fossil fuels and the chemical reactions involved in transforming iron ore into steel.

The transition to CO_2-lean production methods aims to align the industry with ambitious climate goals and create a more sustainable future for European steel production. Consequently, a shift from carbon-based reduction to a hydrogen based direct reduction and a move away from the BF to other technologies, such as DR-ESF-BOF or DR-EAF becomes a necessity. The transformation of the processes has a direct impact on the reduction of greenhouse gas emissions, if clean electricity is used. In addition, several additional measures are being implemented to reduce CO_2 emissions in the steel industry including the development of alternative processes or process combinations (e.g., (hydrogen-based) DR, smelter [14] (i.e., submerged arc furnace or open slag bath furnace types), hydrogen plasma smelting reduction [15, 16], iron ore electrolysis (electrowinning [17], molten oxide electrolysis [18])), as well as carbon capture and usage [19] (and / or storage) technologies or the replacement of fossil-based carbon by bio-based carbon. [20]

[14] Primetlas Technologies: Online: www.primetals.com/press-media/news/primetals-technologies-and-rhi-magnesita-develop-new-melting-technology-for-low-grade-dri (accessed on 31 January 2024).
[15] Naseri Seftejani M. and Schenk J.: Fundamentals of hydrogen plasma smelting reduction (HPSR) of iron oxides, a new generation of steelmaking processes, 2018.
[16] voestalpine, Online: www.voestalpine.com/blog/en/sustainability/greentec-steel-en/research-projects-for-green-steel-production/#:~:text=Sustainable%20Steelmaking&text=In%20just%20a%20single%20process,called%20hydrogen%20plasma%20smelting%20reduction. (accessed on 31 January 2024).
[17] Siderwin project, Development of new methodologies for industrial CO_2-free steel production by electrowinning, Online: www.siderwin-spire.eu/ (accessed on 31 January 2024).
[18] Bosten Metal: Online: www.bostonmetal.com/green-steel-solution/ (accessed on 31 January 2024).
[19] thyssenkrupp: Online: www.thyssenkrupp-steel.com/en/company/sustainability/carbon2chem/carbon2chem.html (accessed on 31 January 2024).
[20] List is not exhaustive.

These measures often go hand in hand with the switch from conventional fossil fuels to low-carbon energy sources. This includes the use of renewable energy sources such as solar, wind and hydro power to replace or supplement the use of coal and natural gas in steel production.

3.1.1 (Hydrogen-based) Direct reduction process

The DR process is a method to produce iron from iron ore without utilizing a traditional BF. The primary raw materials for DR are iron ore pellets, lump iron ore, fine ore or a combination of these. The process can utilize different types of reducing gases (e.g., natural gas, hydrogen) to reduce iron ores into metallic iron (DRI), which is used in melting facilities (e.g., EAF, open slag bath furnace, smelter) to produce a wide range of high-quality steels. DR can be combined with CO_2 capture (and utilization) technologies.

There are different types of DR reactors and the choice between these depends on factors such as the quality of the iron ore feed, production capacity, and cost considerations. Common processes for DR utilizing a shaft furnace are the MIDREX process[21], Tenova's HYL[22], iBlue® [22] and ENERGIRON® [22]. Further possibilities for the DR process are the DR with a fluidized bed (e.g., FINEX, Circored or HYFOR[23]) or by means of a kiln.

DR processes and EAFs are proven technologies. Depending on which technology is used for DR process, the technology readiness level (TRL) for the DR process is between 7 and 9. While melting of carbon-free DRI currently is not common practice in the industry (whether high grade via EAF or low grade in smelters or open slag bath furnaces), and although possible this should be considered as a lower TRL in the industry.

3.1.2 Smelter, submerged arc furnace and open slag bath furnaces

Currently, DR methods demand a high quality of iron ore with low levels of impurities[24], and only a small number of ores are fulfilling these requirements to produce high-quality DRI. Consequently, several steelmakers are researching and developing novel technology (combinations) to facilitate a utilization of lower-grade iron ores in the DR process. The addition of a melting stage to melt the DRI before charging it in a BOF rather than an EAF to make high-quality steel could be a promising strategy. The electric melting stage is suitable for eliminating even a large amount of gangue from the iron ore in the form of slag and produces a hot metal like from a BF, that, as mentioned before, can be further treated in a BOF.

Melting units that can be used for this purpose are, for example, a submerged arc furnace, an open slag bath furnace or a smelter.

The submerged arc furnace has been used mainly in the non-ferrous sector to produce e.g., ferrochromium, zinc, or manganese. The location of the electrodes within the furnace is the primary distinction between a submerged arc furnace and an open slag bath furnace. Whereas the electrodes in a submerged arc furnace are submerged in the raw materials, the electrodes in an open slag bath furnace are located on top of the melt and create an open arc or brush arc[25].

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[21] Midrex: Online: www.midrex.com/ (accessed on 05 February 2024).
[22] Tenova: Online: tenova.com (accessed on 05 February 2024).
[23] Primetals Technologies: HYFOR pilot plant under operation – the next step for carbon free, hydrogen-based direct reduction is done, 2021, Online: www.primetals.com/press-media/news/hyfor-pilot-plant-under-operation-the-next-step-for-carbon-free-hydrogen-based-direct-reduction-is-done?utm_source=metalsmagazine (accessed on 01 February 2024).
[24] Nicholas S. and Basirat S.: Iron Ore Quality a Potential Headwind to Green Steelmaking: Technology and Mining Options Are Available to Hit Net-Zero Steel Targets, 2022.
[25] Nicholas S.: Solving Iron Ore Quality Issues for Low-Carbon Steel: Technology Solutions Are Under Development, 2022.

The smelter technology is based on the already existing submerged arc furnace. The smelter is flexible and can manage low-grade pellets and hot compacted iron or DRI from hydrogen-based DRI ore fines. The smelter is also capable of adjusting the carbon level of the output material and can be integrated into existing steel plants. The smelter process produces slag similar to that of the BF. [26]

At the moment the TRL for the smelter is around 7 and should reach 8 or 9 by the end of 2030 the latest.

3.1.3 Hydrogen plasma smelting reduction

The hydrogen plasma smelting reduction uses ionized hydrogen to convert iron oxides directly into liquid steel. Pre-treatment of the ore used is not necessary, thus compared to the conventional BF-BOF route, coking plants, sinter plants would not be required.

The TRL of this technology is estimated at 6 to 7 in 2030 and 9 in 2050.

3.1.4 Iron ore electrolysis

Low temperature alkaline iron ore electrolysis, also known as electrowinning, entails the direct deposition of iron from its ores onto an electrode. This involves passing a current from an inert anode through a liquid alkaline solution containing small iron particles, which deposit and reduce on the cathode. The approach creates an iron-like material that must be melted in an EAF before proceeding with the standard steelmaking process. The feasibility of low temperature iron ore electrolysis is evaluated at TRL 4 and as part of the SIDERWIN project (2017 - 2023) a 3-meter-long pilot plant was to be developed to validate the technology at TRL 6 [17, 27].

Molten oxide electrolysis is an electrometallurgical technology that allows for the direct synthesis of metal in liquid form from oxide feedstock. It is a fully electrified pathway from unprocessed iron ore to liquid steel, with a single-step process involving the decomposition of iron ore and the melting of iron metal, similar to aluminium electrolytic cells. There are differing estimates regarding the current TRL level of this technology; one source states that it is between 3 and 4 [28], while another notes that semi-industrial molten oxide electrolysis has been validated for steel production throughout 2022 and 2023, and plans are in place for commercial deployment in 2026 [18].

3.2 Circular economy practices

The circular economy approach involves the recycling and reusing of steel products to minimize the demand for raw materials and reduce the environmental impact of steel production. This can be achieved for instance through improved scrap collection, sorting, and recycling processes, enhanced recycling of steel mill residues (e.g., slag, dust) for secondary uses and by creating synergies with other industries.

3.3 Increased energy efficiency

Enhancing energy efficiency in steel manufacturing processes helps to reduce overall energy consumption and, consequently, lowers CO_2 emissions. Implementing advanced technologies, such as heat recovery systems, and optimizing production processes are essential steps in achieving improved energy efficiency.

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[26] Primetals Technologies: Metals Magazine: Innovation and technology for the metals industry, Special Edition METEC 2023, 2023.
[27] World Steel Association: Fact sheet: Electrolysis in ironmaking, 2021.
[28] Aboulhosn A.: Resource efficient manufacturing within the steel industry – A study of the approaches utilized by steel manufactures to optimize resource efficiency, 2023.

3.4 Strategies of individual steel producers and plant manufacturers

Companies in the steel industry are actively engaged in initiatives to address climate change and reduce their carbon footprint by exploring various strategies to decarbonize steel production. The following subchapters provide a summary of the strategies of various steel producers and plant manufacturers. All of these companies are addressing the topics of circular economy, renewable energy and carbon-neutral steel production. Companies that already operate one or more EAF(s) are also focusing on the topics of process optimization, digitalization and the application of artificial intelligence. Companies that currently produce steel using the BF-BOF route are primarily working on the replacement of this route with a DR-EAF route. The companies are listed in alphabetical order [20].

3.4.1 Steel producers

ArcelorMittal (InSGeP partner) operates 47 BFs globally, accounting for 80% of their total steel output in 2020 and 32 EAFs producing 20% of their total steel output [29]. The company is committed to reach net-zero emissions on a global basis by 2050. Their roadmap features five levers which are steelmaking transformation, energy transformation, increased use of scrap, sourcing clean electricity and offsetting residual emissions (Figure 3). In Europe, their strategy is largely focused on the DR pathway [29]. The DR-submerged arc furnace technology path is another option the company is currently researching [25].

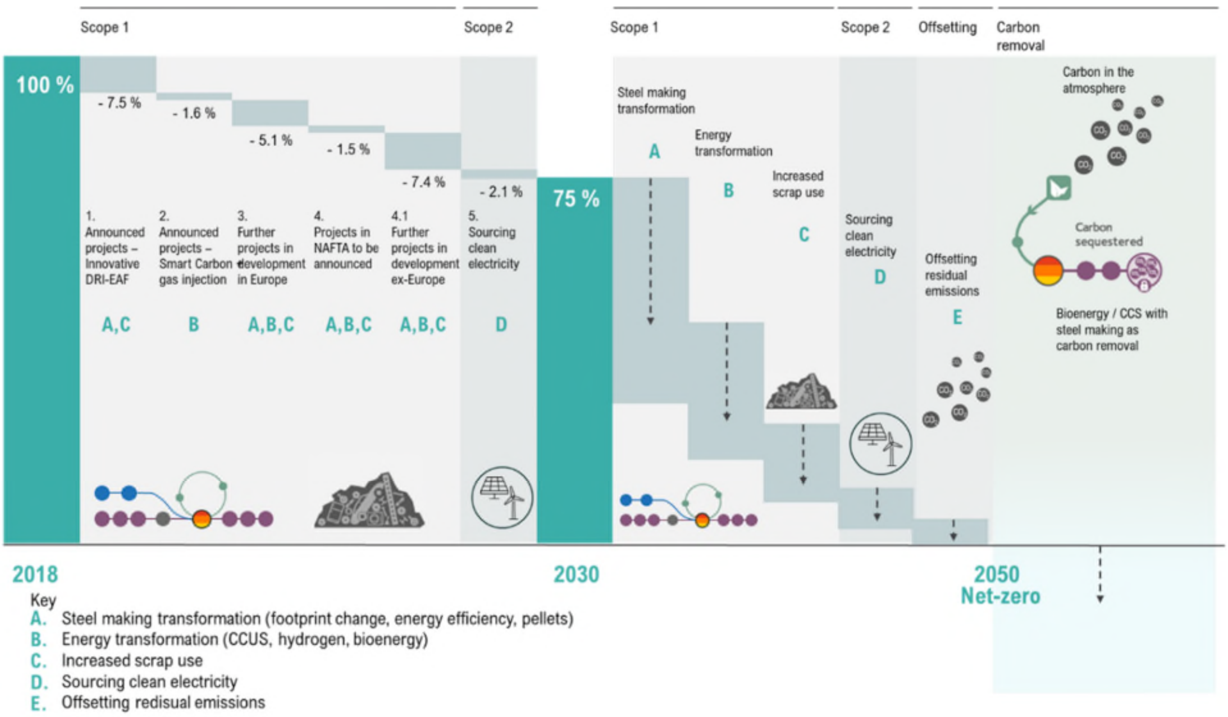


Figure 3: ArcelorMittal's decarbonisation strategy (based on [29])

ORI Martin (InSGeP partner) is an integrated steel group which produces high-quality steel for the automotive, fastener, mechanical and building sectors. The company developed into an electric furnace steel mill to produce continuous casting billets and hot rolled wire rod, bars in coils and alloy steel bars for special applications. It currently operates a Consteel® electric furnace (Figure 4), which involves scrap preheating systems.

[29] ArcelorMittal: Climate Action Report 2, 2021.

Figure 4: Consteel electric arc furnace at ORI Martin [30]

In addition to that, ORI Martin already employs a heat recovery system (Tenova's iRecovery® plant [31], Figure 5) for primary fumes from the melting furnace as well as one from the cooling circuit water with heat pump (Tenova's Life Project "Heatleap" [32], Figure 6), which are both at TRL 9.

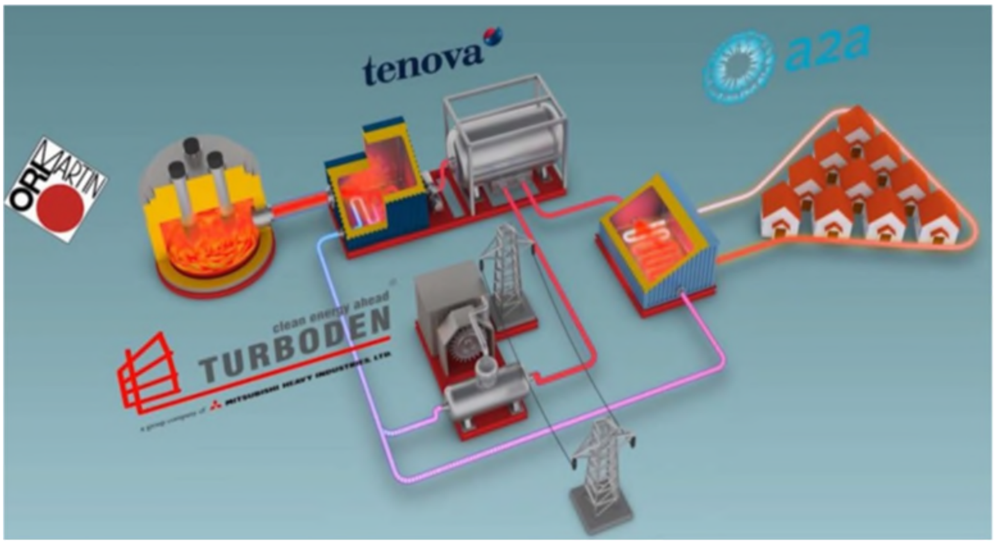


Figure 5: iRecovery® project [30]

During the winter, the iRecovery® system successfully feeds thermal energy to the district heating grid while also feeding an ORC turbogenerator, which produces electric energy for ORI Martin's internal needs [33].

[30] Provided by Ori Martin.
[31] ORI Martin: Sustainability Report 2022, 2023.
[32] Heatleap project: Online: heatleap-project.eu/heatleap-project/ (accessed on 01 February 2024).
[33] Tenova: The two companies started their co-operation in 1998 with the supply by Tenova of the first Consteel® in Europe, Online: tenova.com/newsroom/latest-tenova/tenova-revamps-its-electric-arc-furnace-eaf-ori-martin-italy, 2023, (accessed on 01 February 2024).

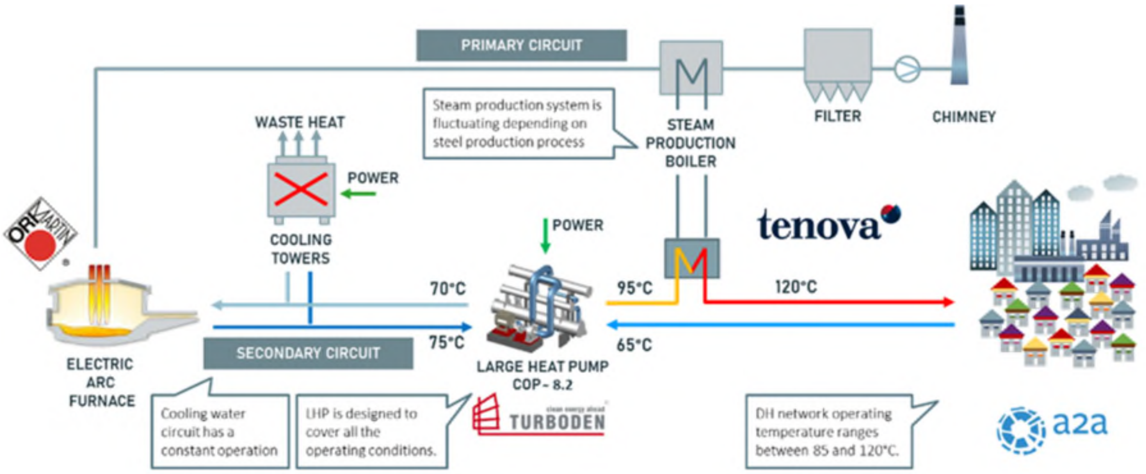


Figure 6: Heatleap project [32]

In the process of the transformation of steelmaking Ori Martin lays its focus on circular economy for both material and energy. This includes the recovery of not only all forms of thermal energy currently wasted and not yet recovered to produce electricity for self-consumption, but also metals from waste from the steel production process and from mechanical processing. In addition, a goal is to employ steel mill slag for secondary uses in accordance with circular economy principles and in synergy with other industries. Ori Martin also aims to reduce consumption in production processes, incorporate more renewable energy, replace methane with biomethane and replace coal with bio coal and polymers. Ori Martin is not planning to make major changes in the steel production plants, as the company already has a process with an electric furnace, but rather focus on the increasingly efficient digitization of control systems, increasing efficiency in manufacturing processes as well as an increasingly important use of machine learning and artificial intelligence.

The **Saarstahl Group** (InSGeP partner), based in Völklingen (Germany), is specialized in the production of wire rod, bar steel, semi-finished products and high-quality forged products. They currently operate two BFs with an annual production of 4.2 million tons of hot metal and supply five BOFs with a total output of 4.9 million tons of crude steel.

Saarland's steel industry (SHS Group) is firmly committed to the climate targets of the EU and the German government to reduce net greenhouse gas emissions to zero by 2045 at the latest and is dedicated to achieving carbon-neutral steel production. To reach these challenging goals, SHS is adapting the long-term transformation process so that SHS has the possibility of achieving a complete technology transformation by 2035 (if technically feasible and economically viable). Figure 7 shows the status quo as well as the planned transformation steps at Saarstahl. Currently, there are two BFs and five BOFs. Saarstahl is also operating an EAF at Ascoval with a production of 0.4 million tons of crude steel.

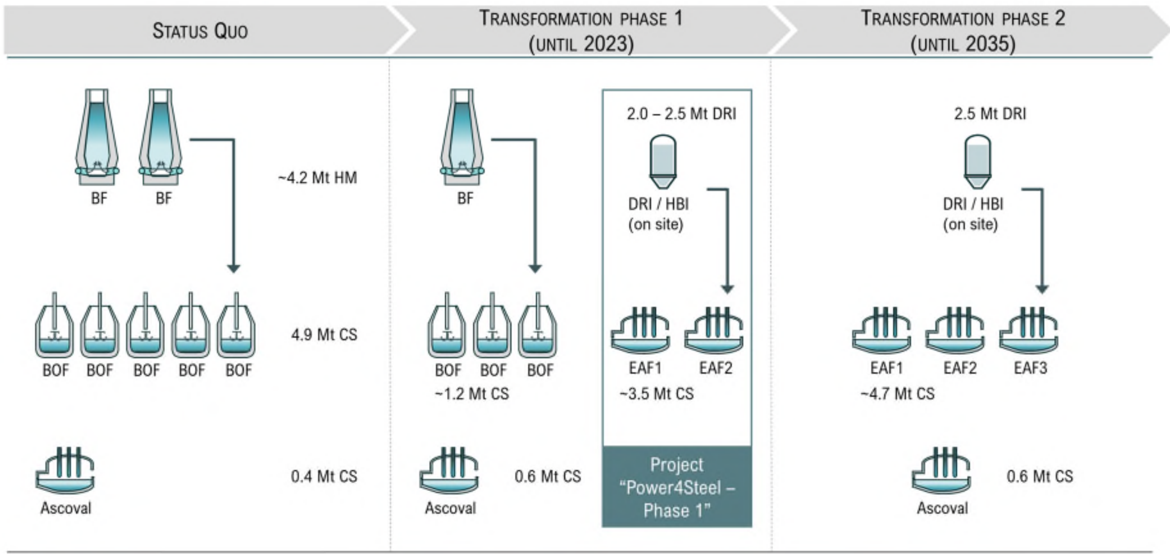


Figure 7: Technology transformation for a carbon-neutral steel industry in Saarland (decarbonization roadmap of the SHS Group; HM… hot metal, CS… crude steel)[34]

In a first step within the context of the "Power4Steel – Phase 1" project, a significant proportion of **Dillinger** and Saarstahl's production volume will be converted to a climate-friendly technology through the installation of a DRI plant and the first EAF capacities. The production capacities of the individual plants are aligned to the site-specific conditions, thus ensuring integration into existing production flows and at the same time achieving the conditions to allow one BF to be decommissioned by 2030 at the latest. With a capacity of 2,000 to 2,500 kt of DRI per year, the DRI plant will be designed so that the entire demand of Dillinger and Saarstahl can be covered as far as possible by the in-house production to be installed at the Dillingen site. The capacity of the two EAF units is determined by the process parameters of the existing steel plants in Dillingen and Völklingen, into which the new technology is to be integrated. This results in a future planned production capacity of 1,700 – 2,000 kt of crude steel per year for the EAF unit in Dillingen and 1,500 – 1,800 kt of crude steel per year for Völklingen. Because one BF must continue to be operated in the transition phase until the technology is fully transformed, steel volumes will also be produced via the existing converter route. However, this will allow converter steel capacities to be scaled down significantly.

Salzgitter AG, one of the biggest steel producers in Germany, operates an integrated steelwork. The strategy 2030 is focused on circularity and the principle of resource-conserving closed loop of energy and materials with a low CO_2 footprint[35]. In order to reduce CO_2 emissions and drive forward climate-neutral steel production the company follows hydrogen-based steelmaking approaches and the conversion of steel production from BFs to DR, initially based on natural gas and later on hydrogen. Salzgitter collaborates with partners on several initiatives, including SALCOS[36] (comprehensive concept for CO_2 reduction), WindH2[37] (green power generated from wind energy), GrInHy 2.0[38] (green hydrogen through electrolysis), and µDRAL[39] (gradual conversion to DR plants).

Salzgitter AG has started making investments to convert an integrated steel production producing 6 million tons annually into a hydrogen-based DR and EAF plant. Using renewable energy to produce

[34] Provided by Saarstahl.
[35] Salzgitter AG: Online: www.salzgitter-ag.com (accessed on 05 February 2024).
[36] Salzgitter AG: Online: salcos.salzgitter-ag.com/en/index.html (accessed on 05 February 2024).
[37] Salzgitter AG: Online: salcos.salzgitter-ag.com/en/windh2.html (accessed 05 February 2024).
[38] Salzgitter AG: Online: salcos.salzgitter-ag.com/en/grinhy-20.html (accessed 05 February 2024).
[39] Salzgitter AG: Online: salcos.salzgitter-ag.com/en/mydral.html (accessed 05 February 2024).

green hydrogen and switching from BF to DR in production, the project's initial phases will reduce emissions by up to 9% by 2033. [26]

Sidenor (InSGeP partner**)** is a special steelmaking company, and its production is notably diverse concerning the chemical composition of its products, which is heavily influenced by customer demand. Throughout the reference year, nearly 400 distinct grades were manufactured, varying in quantities from as low as one to as many as 250 heats per grade. Notably, even within a single steel grade, considerable disparities exist in the chemical composition specified by different clients.

The production route of Sidenor is the 100% scrap based EAF production route. So far, no devices need to be replaced in the transformation process, but one focus lies in adapting the 100% scrap-based production to a partial utilization of HBI. Furthermore, all the existing processes and sub-processes linked to EAF will be reviewed and updated according to what environmental, quality, safety and operational control parameters indicate. In addition, strong efforts are being made on scrap shoring and handling (for example by the digitalization of the yard for an improved tracking of scrap) and by participating in research projects such as RFCS SUPERCHARGEEAF [40] or H2020 REVaMP [41].

Sidenor's roadmap is based on continuous optimization of process efficiency and energy use, as well as on development of more sustainable steels. Milestones such as 100% renewable electrical energy consumption by 2030 or replacement of 100% fossil coal by 2050 can be highlighted. Sidenor intends to recycle 90% by 2025 and 95% by 2030 as part of its circular economy goals. Regarding the climate change targets, the company targets a 55% decrease in greenhouse gas emissions by 2025, 60% by 2030, and to be carbon neutral by 2050.

thyssenkrupp is actively working to replace CO_2-intensive production methods with environmentally friendly solutions. The company has already begun green transformation in its steel sector and is developing its first DR plant [42]. As part of a new steelmaking pathway that will be implemented by thyssenkrupp, DRI production will be followed by a submerged arc furnace melting stage before being sent to an existing BOF. By 2045, the company plans to replace four BFs with new DR-submerged arc furnace installations; the first two will be replaced in 2025 and 2030, respectively. [25]

Furthermore, the company wants to lower its CO_2 emissions by 30% by 2030 and aims to manufacture 0.4 million tons of "green steel" by 2025 and 3 million tons by 2030. With a 1.2-million-ton capacity, the first DRI facility will initially use natural gas as the reducing agent before moving to hydrogen. [43]

voestalpine Stahl GmbH (InSGeP partner) in Linz (Austria) is a business unit in the Steel Division of the voestalpine Group operating a fully integrated steel mill with an annual capacity of 5.9 million tons of steel for flat products. The core aggregates include one coke oven, a sinter plant, three BFs and three BOFs (Figure 8). voestalpine manufactures and processes high-quality hot-rolled and cold-rolled, electrogalvanized, hot-dip galvanized and organic-coated steel strip.

[40] SUPERCHARGEEAF, Supervision of Charge Material Properties in EAF steelmaking Utilising Advanced Statistical Methods, RFCS, 2017-2020.
[41] REVaMP project: Online: revamp-project.eu (accessed on 31 January 2024).
[42] thyssenkrupp: Online: www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/thyssenkrupp-drives-forward-decarbonization-of-emission-intensive-industries-at-cop28-241281 (accessed 05 February 2024).
[43] thyssenkrupp: Electrical hot metal from blast furnace 2.0: thyssenkrupp presents Federal Economics Minister Altmaier and State Premier Laschet innovative concept for green transformation of Duisburg steel mill, 2020.

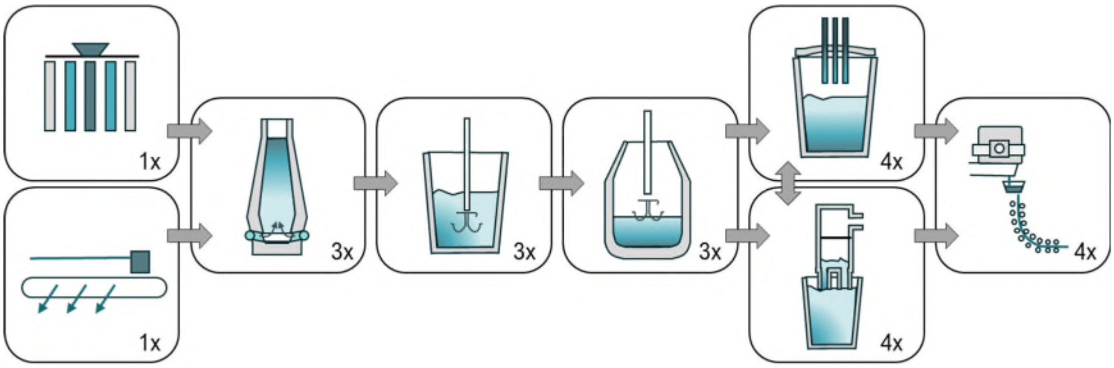


Figure 8: Plant availability at voestalpine Stahl GmbH [44]

Within the year 2027 voestalpine plans to substitute one BF with an EAF. Due to this transformation step more than 1.5 million tons of CO_2 emissions can be reduced. Due to the fact that the electricity in Austria is mainly produced out of water there will be nearly no additional indirect CO_2 emissions. For the year 2035 it is planned to erect a second EAF and to shut down one more BF. Then the last BF (3 million tons per year) will be in operation with two BOFs and two EAFs with 1.5 million tons production each. In a further transformation step – perhaps smelter operation – it is planned to additionally erect a DR production plant. The operation of EAF for "high quality" raw materials, and a smelter operation for "low" quality materials is expected. For EAF operation around 0.5 million tons of HBI are needed per year. For the complete transformation around 3 to 4 million tons of DRI / HBI will be needed.

3.4.2 Plant manufacturers

As an engineering company **Primetal**'s (InSGeP partner) goal is to provide an individual solution for decarbonization of each steelmaking facility based on raw material and product mix. They are building future steelmaking, metal and slag analysis, quantities, and usage from customers next generation steel plants. The target is clear to get from the BF-BOF route to a DRI shaft-smelter-BOF (EAF) for low quality ore and DRI shaft-EAF route for high quality ore. Primetals is developing its own technology HYFOR and EAF updates are done for lower energy consumption and higher heat size. Another new development is the smelter for low grade DRI where currently prototypes for each scale-up from a 2 t/h, a 40 t/h, and an industry sized 150 t/h furnace are planned. The TRL is around 7 and the target is to operate these furnaces by 2030.

Primetals has the goal to support their customers in the transformation process towards green steel. Depending on the plant, infrastructure, raw material, and product portfolio there can be many different solutions.

- Optimization of existing BF-BOF route with higher scrap rate in BOF for automotive high end steel grades with low grade ores
- Integration of EAF in existing BF-BOF plants instead of BF and BOF or as premelt to the BOF
- Complete replacement of BF with a 2 step DRI-smelter-BOF route for low grade ores
- Complete replacement of BF and BOF with DRI-EAF for high grade ores and less critical automotive grades

Tenova (InSGeP partner) is an engineering company, focusing on technology consulting, plant design and supply for the metals and mining industry. Tenova is part of the Techint Group, whose core business is steel production through the Tenaris and Ternium brands. Tenova's portfolio of solutions is dedicated to the sustainable transformation of the metal and mining industries. They create value for their clients

[44] Provided by voestalpine Stahl GmbH.

by providing innovative technologies that ensure efficiency, resulting in better performance, less waste, and lower carbon emissions. They provide technologies that support the transition to cleaner fuels, utilize energy more efficiently, and recover and reuse previously wasted material. Tenova fosters the change of the energy paradigm in the metal industry by proposing alternative production cycles and promoting the use of hydrogen-ready technologies to its customers for the transformation process of their operations.

ENERGIRON® is the innovative HyL DR technology, jointly developed by Tenova and Danieli. It has been designed to use different types of reducing gas sources or pure hydrogen to reduce iron ores into metallic iron, to be used in melting facilities to produce a wide range of high-quality steels. ENERGIRON® plants have the further advantage to selectively remove CO_2 to achieve the lowest carbon footprint.

iBlue® is one of Tenova's answers to the global steelmaking decarburization challenge. As a technology for low carbon emissions hot metal production, it combines ENERGIRON®'s DR process with EAFs. The result is the production of hot metal to feed steel processing plants downstream of iBlue®, and the production of granulated inert slag saleable to the construction sector or other industries. Main characteristics of Tenova iBlue® are:

- Ability to process BF grade and DR grade pellets;
- Regardless of gangue content, produce a slag saleable to cement industry;
- Integrated gas management - the CO-rich furnace gas is recycled to the ENERGIRON® process gas heater, reducing the overall plant energy requirements;
- Ability to produce high carbon hot metal for use in existing BOF and
- Tenova's patented dry gas cleaning technology, further reducing the environmental impact of the process plant.

Tenova promotes the transition towards a green steel industry and supports customers in the transition from carbon intensive BF technology by offering modern systems to optimise the existing production cycle offering:

- Hydrogen ready DRI production facility and EAF melting facility in substitutions of BF-BOF
- Hydrogen ready DRI production facility and open slag bath furnace melting facility in substitution of BF (iBlue®)

3.5 Change of input materials and implications

Figure 9 illustrates the global projected volume of steel production by route until 2050. It indicates that, over time, the share of the BF-BOF route is likely to decline, while the share of the scrap-based EAF route is expected to increase.

Due to various trends for next generation steelmaking, the focus for input materials is increasingly on scrap and DRI / HBI. Furthermore, by applying the concepts of circular economy, the charge of the EAF will be increasingly composed of not only scrap but also recycled materials such as flakes, rolling sludge, flue gas dust, etc., all of which will recover metals from waste but will complicate the scrap melting stages by increasing the amount of slag produced.

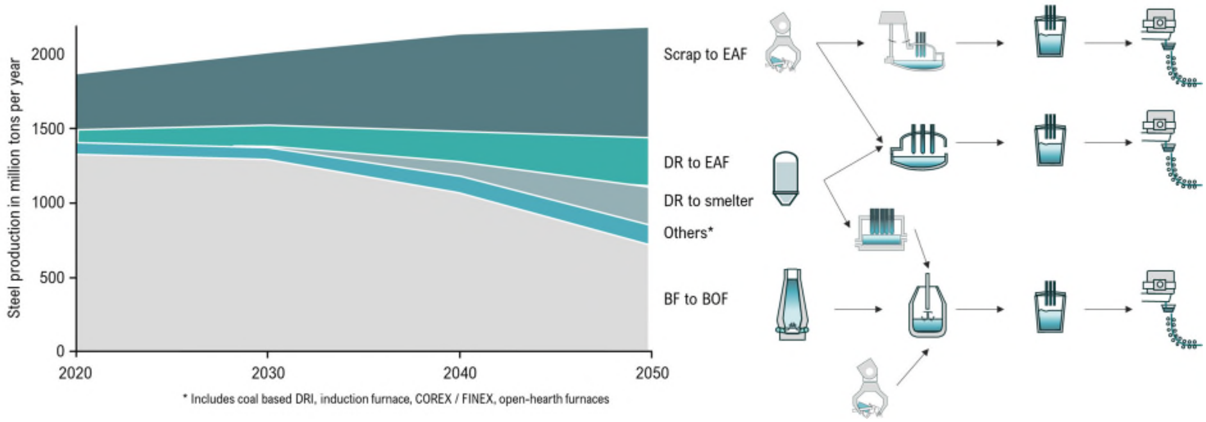


Figure 9: Global steel production volume by route (based on [26])

An increase of the amount of DRI / HBI used and the general worsening of the quality of the metal charge (including scrap) will lead to several changes in the EAF process including:

- Increase of energy demand, reflecting in higher consumption and consequently higher power requirements
- Need of a different slag engineering, leading to the increase of slag forming additives
- With the use of DRI as source of virgin iron units and the replacement of BF by DR plants, the pig iron will become more expensive and therefore the use of chemical energy will reduce.
- Processes that can guarantee high carbon DRI therefore enable the production of higher carbon DRI to be used as a replacement of pig iron (presumably at higher prices than low carbon DRI)
- Considering the evolution of the cost of metallics, the new EAFs will need to take care of reducing iron losses to the minimum (therefore a flat bath process will most likely substitute the traditional batch-charges process) allowing a longer reaction time between slag and metal and possible precipitation of reduced FeO in the bath
- Increase of black-slag production because of the use of higher quantities of DRI
- Increase of the dimension of reactors
- Increase of energy content in off gas will consequently lead to a wider utilization of energy recovery systems
- Increase in the performance of refractories and coolers
- Increase in the transformer power
- More holistic approach to the “performance” of the plants, not just considering production and consumption parameters, but also total CO_2 footprint, circularity of all components used in production will lead to new key performance indicators
- Increase in the use of advanced automation and artificial intelligence in order to refine process conditions, adapt them with time and maintaining plant competitiveness while achieving an optimized environmental impact
- A wider attention to emissions will lead to the implementation of systems that will control other noxious elements that today are not monitored regularly and therefore to the installation of more advanced off gas treatment plants.

(Cold) DRI and HBI will increase the energy consumption of the EAF and require a hot heel as processing times with (cold) DRI and HBI are longer than with pure scrap-based EAF at less productivity. Based on the metallization and gangue content the energy consumption is roughly 100 to 200 kWh/t higher with DRI than with scrap. Also, refractory lifetime is shorter due to higher slag amounts and a lower basicity of the slag compared to scrap-based EAF.

A further issue arises with the specification for phosphorus, a requirement that many of the steels must also meet. This compels the use of HBI with the lowest possible phosphorus content. The utilization of

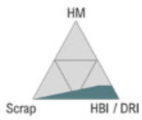
HBI with high phosphorous content would necessitate a conscientious adjustment of timings, processes, and facilities to accommodate higher lime consumption, leading to an increased volume of generated EAF slag. It is important to note the economic impact of this outcome, simply due to the extended melting time or, in other words, the loss of productivity.

Lower carbon content in the DRI will require additional carbon for the EAF operation to do the final reduction of iron oxide and for application of foamy slag.

The advantage of DRI / HBI based EAF operation is the consistent chemistry (high grade ore) with less impurities and trace elements than scrap. In addition, DRI / HBI based EAF can be operated with flat bath, continuous foamy slag and more gas transport through the melt which all is limiting the nitrogen content.

The following table (Table 1) gives an overview of different key performance indicators of typical reference data from BOF and EAF operation.

Table 1: Comparison of typical reference data from BOF and EAF operation [45] (KPI … key performance indicator, KOBM … Klöckner Oxygen Blown Maxhütte converter)

KPI	Unit	BOF	KOBM	Scrap EAF	Flexible EAF	DRI EAF
Typical charge mix						
Hot metal / scrap / direct reduced iron	[%]	80 / 20 / 0	65 / 30 / 5	0 / 100 / 0	40 / 40 / 20	0 / 30 / 70
Yield	[%]	90.5	91.5	89.0	89.5	87****
Tap to tap time	[min]	40	40	50	45	55
Nitrogen level EOT*	[ppm]	16 – 50	16 – 50	60 – 100	35 – 80	25 – 60
Refractory lifetime	[heats]	~4000	~4000 (2000**)	500 – 1500	500 – 1500	~1000
Energy output / heat losses	[%]	20 – 30	20 – 25	35 – 40***	40 – 45	45 – 50
Slag	[%]	13	10	13	12	18
Offgas	[%]	9	8	12 – 18***	18 – 28	18 – 28
Cooling water & others	[%]	3	3	10	10	10

* End of treatment (before tapping)
** Hot bottom exchange
*** Depending on scrap preheating
**** Direct reduction grade pellets, lower for blast furnace grade direct reduced iron

3.5.1 Scrap

The output of the EAF process is highly dependent on the quality of the input materials. As a larger part of the steel production becomes scrap-based, tramp elements gradually accumulate in the feedstock and the scrap quality will deteriorate over time. However, if scrap-based processes become more prevalent, less dilution will occur, and the problem will worsen. Considering the decarbonization pathways currently in planning and implementation, it is foreseeable that the future will witness not only a reduced availability of scrap but also a continual decline in its quality.

Today, scrap is sorted into streams based on likely contamination and is shredded or cut to separate pieces using techniques based on magnetic fields and density. While this has been sufficient up to now, an increased reliance on scrap feedstock, the possibility of material being recycled multiple times,

[45] Provided by Primetals Technologies.

increasing electrification (and so more machines containing more copper wires), and the ever-higher demands on materials performance demand to enhance the control of tramp elements.

Contamination by unwanted elements (e.g. copper, phosphorous, tin) can be very detrimental to the properties of special steel in its final application. Such effects are apparent even during manufacturing, where material can undergo surface failure during rolling and forging. Low-quality scrap cannot be refined during smelting and refining (e.g. decrease in waste elements or sulfur content).

The elements examined in Table 2 can be classified into the following matrix that crosses their impact on final product properties and elimination feasibility in the steelmaking process.

Table 2: Matrix crossing impact of different elements on the final product properties of steel [46]

		Harmfulness for final steel production		
		Low	**Medium**	**High**
Difficulties to be removed in the EAF	**Low**	Mn	-	-
	Medium	Cr	-	P
	High	Ni, Mo	S	Cu, Sn

Controlling the composition of the scrap mix destined for the EAF involves critical considerations for several elements.

- Copper stands as a pivotal element demanding control in the scrap mix for the furnace. Once introduced, copper remains inseparable from the steel during subsequent stages of the steelmaking process.
- Tin, although present in lower concentrations compared to copper, is an unwanted element coming from protective layers in scrap. It can lead to defects associated with "hot shortness" in the steel product.
- Sulphur, known for its detrimental impact on metallurgical processes as well for its tendency to cause embrittlement at high temperatures, can be reduced in the secondary metallurgical stage. Optimizing the scrap charge to minimize sulphur input aids in enhancing productivity by reducing desulphurization time and decreasing slag production.
- Phosphorus is another undesirable element that can only be eliminated under specific oxidizing conditions in the EAF. However, its high content negatively affects the key performance indicators of an EAF like productivity and slag generation.
- Manganese and chromium serve as common alloying elements in steel production due to their hardenability properties. Their oxidation in the furnace and transfer to the EAF slag, coupled with their economic advantage over other alloying elements, typically exclude them from the metallic load. It is to be noticed that the presence of chromium oxide in the slag adversely impacts the environmental performance and potential utilization of this by-product.
- Nickel enhances toughness and diminishes cracks and quenching distortions in steel. Its higher cost compared to chromium makes a selective inclusion of nickel-rich scrap for specific steel grades necessary.
- Molybdenum, offering improved hardenability beyond chromium and nickel, is commonly employed for hardening, quenching and tempering grades. Its relatively high price compared to both chromium and nickel leads to the use of molybdenum-rich scrap when required.

[46] Provided by Sidenor.

In summary, the challenge of utilizing low-quality scrap lies in the contamination of scrap by residual (tramp) elements that resist removal in the EAF. Among these elements, copper and tin pose significant challenges due to their high probability of contaminating recycled low-quality scrap.

3.5.2 Direct reduced iron / hot briquetted iron

EAF technology is already highly developed, and the use of DRI / HBI is largely consolidated. However, with the changes in the next generation steelmaking and the rising usage of hydrogen, it is vital to understand the behavior of DRI / HBI of varying quality and generated with hydrogen. The increasing use of hydrogen in the production of DRI will require different fusion procedures given the absence of carbon in the pre-reduced mixture.

From an environmental point of view, there are uncertainties about how HBI will impact EAF dust and slag composition / properties and the final greenhouse gas emissions balance. On the economic side, it is assumed that costs related to EAF process will probably increase due to the higher price of HBI compared to scrap, the higher consumption of electrical energy, lime, electrodes and other resources. Additionally, well-designed storing and handling facilities have to be implemented. Also, suitable HBI distribution in the basket must be defined.

In the scenario of using 10% HBI as an alternative to the currently available cleaner scrap, it is anticipated that there will be an increase in electricity consumption, leading to greater electrode wearing. Additionally, there is likely to be higher lime consumption due to oxides such as silicon oxide present in the gangue, resulting in increased wear of EAF refractories. Considering the loss of productivity, it is estimated that this scenario could entail additional costs on the order of € 25 per ton of good billet steel. Therefore, in the scenario of a special steel producer with an installed capacity of 1 million tons annually and one-third of its production mix requiring low phosphorus, the utilization of HBI at the aforementioned rate is projected to incur an additional annual cost of approximately € 8 million.

4 Conclusion

The European steel producers are aware of the required change towards CO_2 neutral steel production. Many companies are planning to substitute one or more BFs with DR and / or EAF technologies. That seems to be realistic as DR and EAF are well-known and proven technologies at large industrial scale. The problem hereby is the fact that not all steel grades can be produced in an EAF with 100% scrap input. Furthermore, the globally available scrap quantity to cover the whole crude steel demand will not be available. Therefore, a certain amount of HBI and / or hot metal will still be required in future to fulfill quantity and quality requirements. Besides that, the amount of high-grade iron ores is limited inducing a higher share of low- and medium-grade ores to be used for DR or hot metal production. That is why further research activities go in the direction of hydrogen-based DR and melting the (low grade) HBI with smelter technology.

So, it can be summarized that the metallurgical transformation is divided in two steps:

1. Partial substitution of BF technology with EAF and
2. Substitute carbon-based reduction metallurgy to hydrogen-based metallurgy.

InSGeP

Investigations of Slag from Next Generation Steel Making Processes

START DATE | 01-07-2023
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CONTACT | d.algermissen@fehs.de