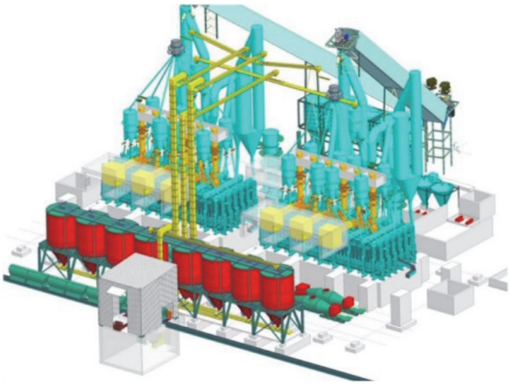
Breakthrough Pathways to Decarbonize the Steel Sector



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Today, the iron and steel sector is the most significant industrial CO_2 emitter, contributing around 8% of global CO_2 emissions. Fossil fuel-based BF (blast furnace) Ironmaking is the primary source of these emissions. Besides the scrap-based EAF (Electric Arc Furnace), hydrogen-based direct reduction shows immense potential to decarbonize the steel industry. Primetals Technologies, as part of MHI Group, is well positioned to facilitate the transition toward green steelmaking with its comprehensive portfolio of direct reduction and steelmaking technologies.

This article presents an overview of different steel production routes and their related CO_2 emissions based on the various iron sources, such as hot metal, DRI/HBI (Direct reduced iron/hot briquetted iron), and scrap. The article discusses transition scenarios, including hybrid EAF-BOF (Basic Oxygen Furnace) steelmaking and new green steel production routes using hydrogen-based direct reduction followed by EAF steelmaking for high-grade DRI, as well as the recently developed two-step process via a SMELTER and a BOF for low-grade DRI.

1. Introduction

The iron and steel sector is the most significant global industrial carbon dioxide (CO_2) emitter, responsible for around 8% of global CO_2 emissions. The global environmental impact of the steel industry is mainly driven by the CO_2 emissions generated during ironmaking via BF, which is still the dominant production route, accounting for approximately 70% of global steel production[(1)].

This coal-based reduction process in the BF and the following oxygen steelmaking process leads to direct CO_2 emissions of approximately 2 tons of CO_2 per ton of steel, of which the hot metal production contributes about 80%. Other charge materials like DRI produced with natural gas emit less than half of these emissions. Hydrogen-based direct reduction is already getting close to net-zero and steel scrap has zero CO_2 emissions (**Figure 1**).

As a first step to reduce CO_2 emissions, steel producers can look toward maximizing scrap rates in existing plants and implementing new scrap-based EAF steelmaking, which has the lowest CO_2 emissions of all steelmaking routes. Depending on the electric power grid factor, green electricity (<80grams CO_2 / kWh), combined with highly efficient EAF technology such as Primetals Technologies EAF Quantum, can reach average crude steel CO_2 emission below 150 kilograms per ton. However, it is impossible to transform the entire steel industry to scrap-based EAF since scrap availability and steel quality limit this production route. Hence the lion's share of steel in future will still require virgin material. However, in an intermediate step of the transformation toward scrap and DRI-based steelmaking, hybrid EAF-BOF steelmaking is an ideal option. For hybrid EAF-BOF steelmaking, the highly flexible EAF FUSION by Primetals

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Technologies is a clear choice. Yet, the iron ore-based charging material DRI presents the greatest potential for green steelmaking.

Primetals Technologies has a broad portfolio for DRI production, including MIDREX, HyREX, or HYFOR (Hydrogen Fine Ore Reduction), which can be applied depending on the ore properties and grain size (**Figure 2**). The quality of iron ore also defines production processes following the production of DRI. Processing high-grade DRI in an EAF is an established route in the market. However, since the availability of high-grade ores is limited and current BF operations utilize low-grade ores, new solutions are required for the final reduction, melting, and refining of lower-grade DRI. A two-step process combining a Smelter to produce hot metal followed by refining in a BOF converter seems to be the most promising solution for low-grade ores. Primetals Technologies is developing and upscaling such a solution in cooperation with refractory supplier RHIM and other partners[(2), (3)].

In parallel to previously mentioned solutions for carbon emission avoidance also CCS (Carbon Capture and Storage) and CCU (Carbon Capture and Utilization) solution will contribute to the Decarbonization of steelmaking industry. Especially for plants which keep the BF in operation CCS will be feasible solution to reduce the greenhouse gas emissions.

The following sections further explore different steelmaking technologies, compare various technologies, demonstrate the implementation of various EAF solutions, and, lastly, detail the new two-step Smelter-BOF process.

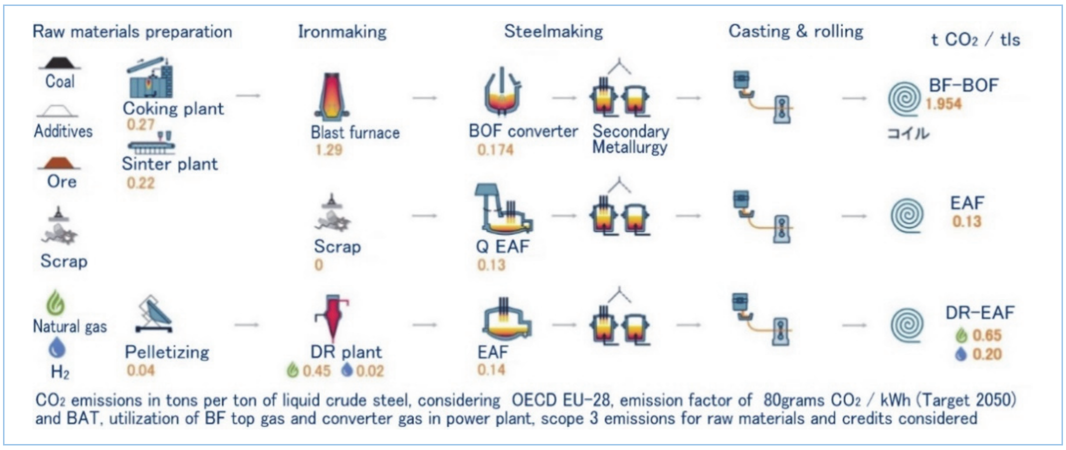

Figure 1　CO_2 emission of typical steel production routes

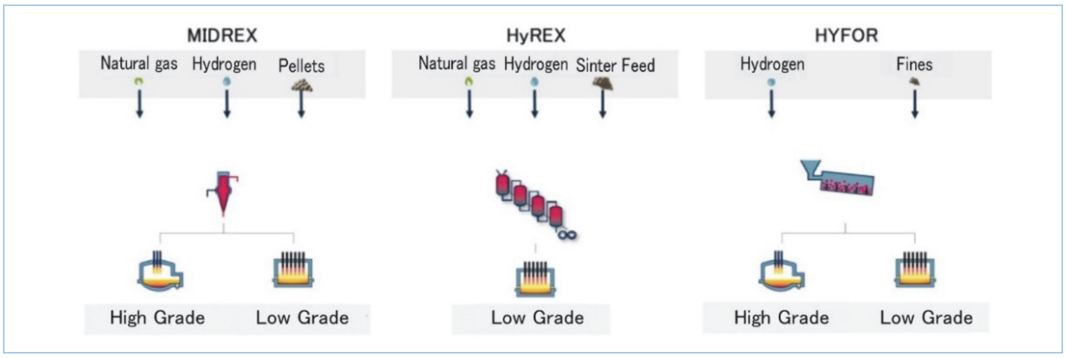

Figure 2　Overview of DRI production technologies and melting aggregates

2. Maximizing Scrap rate in integrated plants and Hybrid BOF EAF Steelmaking

Increasing the scrap rate in existing BOF plants is an efficient, ready-to-implement solution to reduce CO_2 emissions, which does not require any infrastructure changes. Multiple solutions, from process optimization to scrap preheating and increased post-combustion, can boost the BOF scrap rate up to 30%. As a result, these solutions reduce the hot metal rate and the CO_2 emission levels by 10-20%. However, the BOF process is an autothermal process without a possibility for external (electric) heating, unlike an EAF. Thus, the lack of an external heat source limits the solid charge rate and CO_2 reduction potential[2]. An EAF is more flexible regarding the charge mix, and the electric energy feed through the electrodes can maintain a solid charge mix of up to 100% of scrap, HBI, or DRI. With furnaces like the EAF Fusion, which can include features like a hot metal launder, additional top blowing lance, and a dedicated upper vessel in the transition phase, high hot metal rates of up to 75% are possible. This feature makes the EAF Fusion an innovative solution for plants that continue operating using BFs or have limited access to scrap and DRI[4].

Yet, incorporating an EAF into existing integrated plants is challenging due to high electric power demand, recertification of steel grades, limitations of existing plant infrastructures, and major changes in logistics and production processes. Especially for larger converter plants with heat sizes of more than 300 tons, a direct replacement of a BOF with an EAF is difficult due to the large transformer size, electric power demand, and longer processing times. For this reason, Primetals Technologies has developed a patent-pending process called PREMELT, where scrap and DRI are “pre-melted” in an EAF, mixed with the hot metal from one of the remaining BFs, and charged into the BOF converter. In the PREMELT process, the EAF focuses on melting, while refining is completed in the BOF. The advantage here is that the heat size of the EAF can be less than that of the BOF. In addition, the location of the EAF is very flexible. It can be placed partially outside the steel plant, which does not require a change in internal steel plant logistics, and steel grade certification remains unchanged in respect to production route. The furnace type and design for the PREMELT process depend on the charge mix and the heat size. For heat sizes smaller than 70 tons, IF (induction furnaces) are capable of meeting melting demands, whereas, for larger heat sizes, which require more power input, an EAF is more efficient. The lowest possible CO_2 emissions can be achieved by applying the scrap-based and highly energy-efficient EAF Quantum. In this furnace lowest energy consumption is achieved by scrap preheating using the hot off-gas. However, a disadvantage of the PREMELT process is that if all BFs are blown down, or production is switched to direct reduction, the EAF type, location, and heat size may no longer fit into the production process and require additional modifications. **Figure 3** shows transformation steps for BF-grade ore-based integrated steel plant toward a hybrid EAF-BOF plant with the incorporation of an EAF, as well as a long-term scenario applying a two-step process for hydrogen-based direct reduction steelmaking.

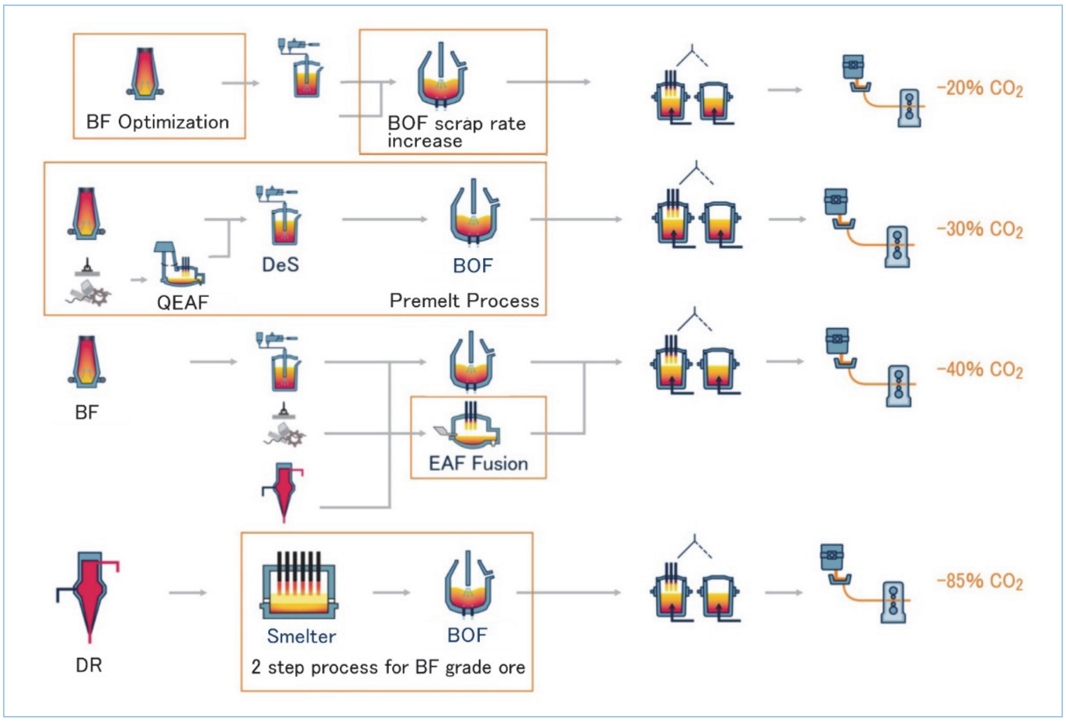

Figure 3 Hybrid EAF–BOF plants and possible routes for the transformation of BF grade ore based integrated steelmaking

3. DRI Steelmaking

Direct Reduction is today the most promising alternative to BF-based iron production to minimize CO_2 emissions. Today, the dominating direct reduction technology is the MIDREX shaft process, which produces DRI pellets using a reducing gas, mainly syngas generated from natural gas and, in future, hydrogen. After this reduction step, the DRI is fed directly into an EAF or briquetted into HBI (Hot Briquetted Iron) for shipping and later fed to BF, BOF, or EAF. Primetals Technologies has installed various DRI-EAF configurations, especially in the Middle East, operating with up to 100% DRI. Compared to scrap-based EAF steelmaking, a high DRI share in the charge mix leads to higher energy consumption and, therefore, longer tap-to-tap times. The main reason is the gangue content and the final reduction of the FeO content in the DRI. On the other hand, a high DRI share allows tapping at lower nitrogen levels due to less or no scrap melting and full foaming slag coverage of the bath.

For the profitable operation of an EAF, high-grade DRI/HBI with low gangue content and high metallization is required. Low gangue content and high metallization keeps the slag amount in the EAF process at reasonable levels and ensures fewer iron losses, lower electric power and flux consumption, and, consequently, a better yield compared to the usage of lower grade DRI/HBI. However, the availability of high-grade ores is limited, and most of the global seaborne ores used for BF operation are of lower grade (**Figure 4**). Therefore, new solutions for processing DRI produced from these lower-grade ores are necessary.

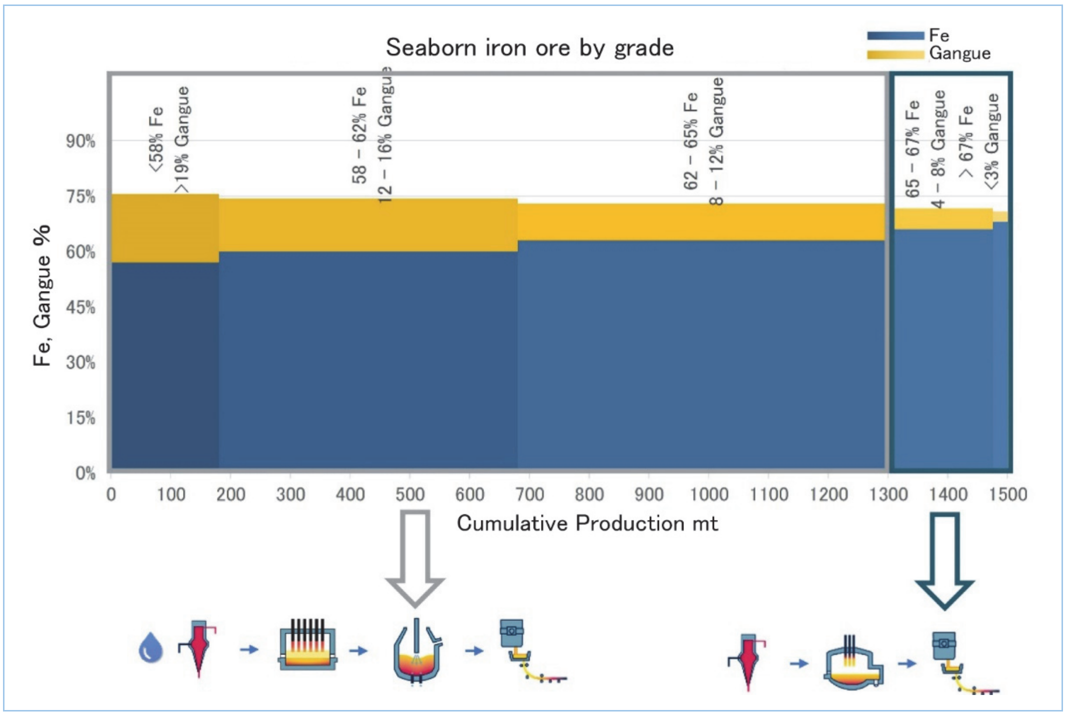

Figure 4 Typical iron and gangue content of seaborn iron ores in 2017 and preferred process route

Lower-grade ore has typical gangue content of 12%, which is more than double the amount of high-grade ores. Higher gangue content will result in higher flux consumption in the EAF to achieve the targeted slag basicity and proper slag foaming. Stable EAF operation with foaming slag requires slag basicity of approximately 1.8, which explains well the increased specific slag amount of more than 400 kilograms per ton in an EAF with lower grade material. The higher slag amount in combination with FeO contents above 20% leads to significant iron losses and, therefore, a low yield. Another topic to be addressed is the utilization and recycling of a large amount of DRI-EAF slag. The common practice is only some limited applications after mechanical separation and internal recycling.

A practical solution can be the processing of low grade DRI via a two-step process with a Smelter and a BOF. In this case, the Smelter performs the melting and final reduction, while a separate second step performs all the metallurgical work and refining, typically in a BOF converter. Splitting the process into two steps allows in the first process step an efficient separation of metal and slag as well as generating a slag suitable for the cement industry. The Smelter can operate at low slag basicity of around one, which leads to a lower slag amount and results in a slag very similar to granulated BF slag. The reducing atmosphere in such a closed stationary furnace will facilitate a high reduction degree and lowest iron content in the slag, which supports a high yield.

Besides the advantages of the higher yield, lower slag amount, and the possibility of using the slag in the cement industry, the existing BOF steel plant operation and downstream processes can be kept intact. The lower costs of low-grade ores compensate for the higher operating cost of the two-step process compared to a one-step process using an EAF(2). **Figure 5** compares the calculated total costs for both production routes for different ore grades on a European price base.

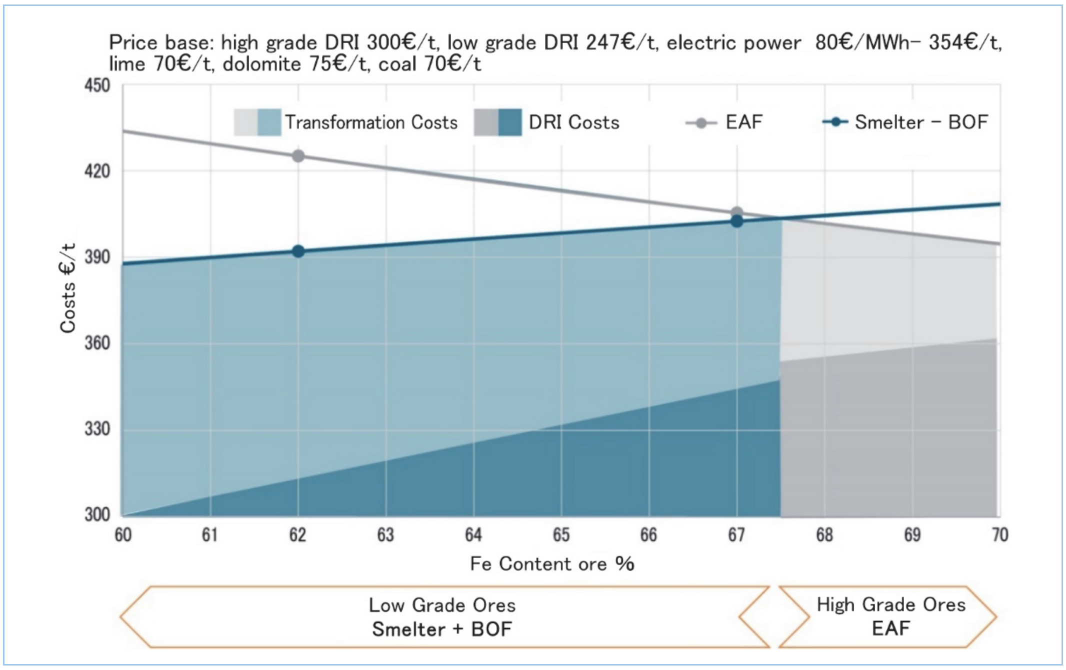

Figure 5 Total cost for EAF and Smelter+BOF production route in relation to the ore quality (Fe content)

For both routes, the transformation cost—mainly electric energy, material additions, and media consumption—increases with lower ore grades. On the other hand, the DRI cost decreases. Figure 5 shows that processing DRI from low-grade ores is cheaper in a two-step process and higher grades are better suited for direct EAF processing. The current market reflects this trend. All DRI-EAF plants today use high-grade DRI and accept the demanded price for such a premium charge material.

Direct reduction-based steelmaking will replace a significant share of current integrated BF-based steelmaking to facilitate greener steelmaking in the future, as indicated in **Figure 6** where possible future share of steel production routes is shown. Both DRI-EAF steelmaking and a two-step process via a Smelter are feasible for green steelmaking. For the integrated steel plants, which want to keep their raw material base with lower grade ores, melting and final reduction in a Smelter followed by final refining in the BOF presents itself as the preferred solution.

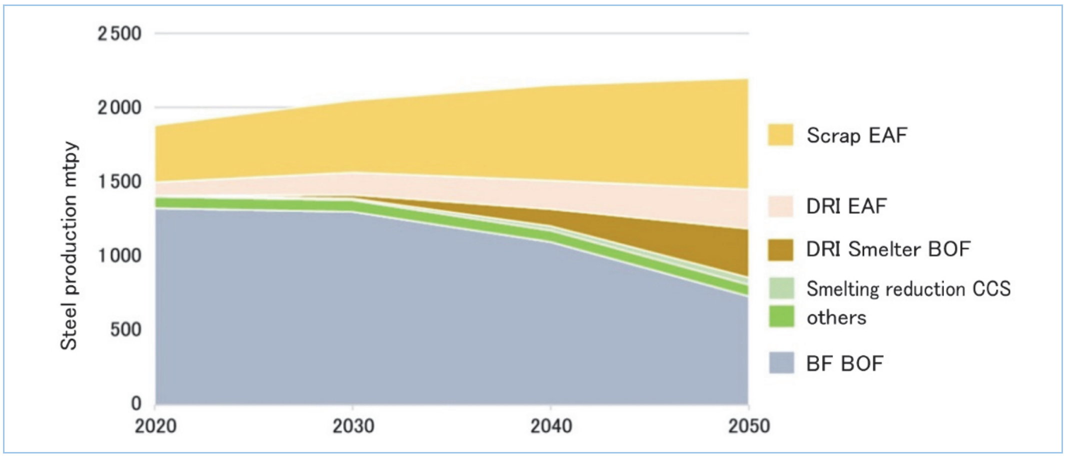

Figure 6 Estimated future share of steelproduction routes until 2050

4. Development and Design features of Smelter

The SMELTER can process a wide range of input materials, from low-grade DRI in the form of pellets or HCI (Hot Compacted Iron), e.g., from a Midrex direct reduction shaft module to DRI fines from a future HYFOR or HyREX. Besides DRI, iron and byproducts containing iron oxide such as dust, mill scale, or slag can be melted and reduced in the Smelter.

The design principle of the SMELTER is a purely electrically heated furnace with a large hot heel. No chemical power input, e.g., Fe oxidation through side wall oxygen injection, is applied, similar to DRI-EAF processes. Resistance heating with Söderberg electrodes generates heat and ensures stable and efficient operation with a long refractory lifetime. In addition, operation with a short arc, or brush arc mode, is anticipated to boost productivity. Still, the total power input per electrode and also the specific power input related to the bath surface is much lower than for a classical EAF, hence larger furnace dimensions are required. The furnace shape can either be round or rectangular. A typical and straightforward refractory concept for a rounded shape furnace can be applied since the wedged bricks arranged in a circle are braced against each other. Due to the thermal expansion of the refractory bricks in a rectangular furnace a pre-tensioning device is foreseen to avoid gaps in the straight lining walls. Pretension devices are based on adjustable fail-safe disc spring concept. The Smelter capacity needs to fit to direct reduction plant capacity where the main sizes are from 1.5mtpa to 2.5mtpa. A rectangular shape furnace with 6-in-line electrodes allows for an annual capacity of up to 1.5mta DRI, hence for a large direct reduction plant two SMELTERS working in parallel are required. Smelters with round design are equipped with three electrodes only and have about half the capacity of a rectangular Smelter.

Figure 7 (below) shows a configuration with two rectangular smelters side by side, fed by one direct reduction module via a hot transport system. Each smelter has a capacity of 1.25mtpa and Söderberg electrodes achieve sufficient power input for the large furnace dimensions. Tapping the metal is similar to a BF via a drilling machine and runners directing the metal into torpedo cars, allowing existing infrastructure to remain intact to transport and handle the melt in the steel plant.

For the development of the Smelter, Primetals Technologies and RHIM have performed detailed process analyses and established the furnace design. The refractory concept accommodates continuous operation with a large hot heel and a cooling system helps achieve long refractory lifetimes of several years. The business case has been evaluated, and multiple customer studies have proven the benefits of implementing 2 step process for low-grade DRI melting. The next step is to validate the process concept in small test campaigns, followed by an upscaling to an industrial prototype plant, preferably in combination with the HYFOR process. While dependent on various factors and lead customers, an industrial demonstration plant will be operational by 2025.

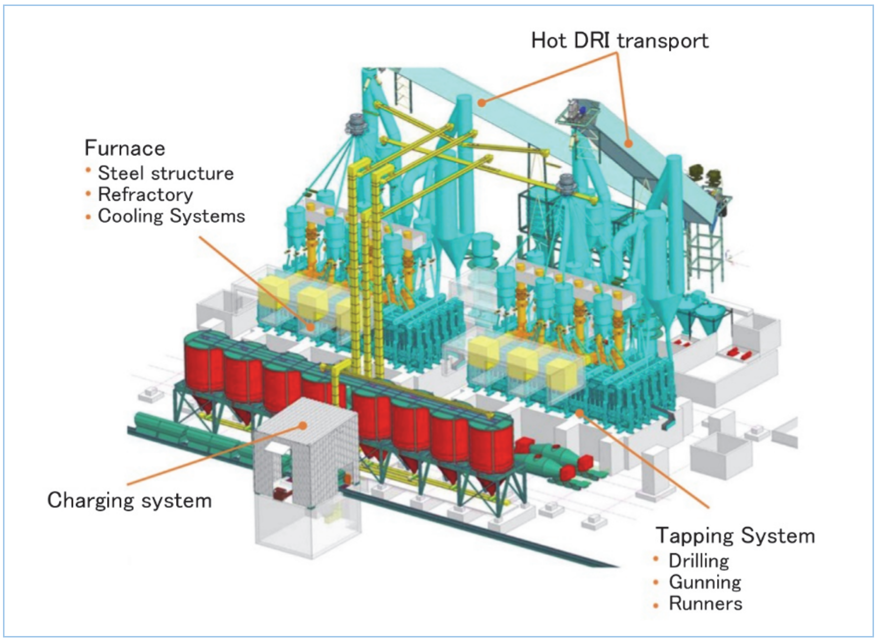

Figure 7 3D Layout and main components of Smelter

5. Conclusion

Decarbonizing the steel industry will require introducing more scrap and direct reduction-based steelmaking to enable the production of green steel and a greening of the steelmaking process. The starting point will be the maximization of scrap rates in existing integrated plants and transitioning to the innovative hybrid scrap-based EAF steelmaking process. However, long-term hydrogen-based direct reduction in steelmaking seems to be the most promising solution for integrated plants. Additionally, depending on the ore quality used, two production routes can be applied. For high-grade DRI, EAF steelmaking is the most feasible decarbonization solution. Whereas for low-grade DRI, a two-step process with a Smelter and further processing in existing BOFs is the more economical solution.

Primetals Technologies has a comprehensive portfolio and extensive knowledge to support the steel industry's transformational journey. Here, the primary portfolio elements such as solutions for an increased scrap rate in existing plants, the Midrex direct reduction plant in combination with EAFs, and innovative solutions still under development and upscaling, such as the earmarking HYFOR technology for direct reduction of ore fines with hydrogen or the SMELTER technology for melting and final reduction of low-grade DRI will define the future of the steel industry.

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