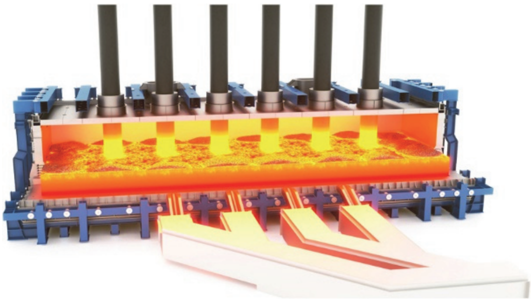
Smelter
Green Steelmaking Using Low Grade Input Materials



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Hydrogen-based direct reduction is expected to become one of the main levers to reduce CO_2 emissions in future iron and steelmaking. For melting and refining of the direct reduced iron typically an electrically heated furnace is used. As most of the iron ores globally are of lower grade and beneficiation has its limits, a new type of furnace–the Smelter—is required. This furnace allows to process direct reduced iron made from low-grade ores in an efficient way, producing hot metal that is refined to crude steel in a converter or charged to an electric arc furnace and a slag suitable for the cement industry. Based on detailed process calculations, the business case for this new process route could be confirmed and furnace design developed. After successful testing two projects for first industrial realization are now under execution.

1. Introduction

The iron and steel industry together with the cement industry are the two largest industrial CO_2 emitters. Most of the emissions are generated during ironmaking which is still dominated by the integrated blast furnace route using coal as primary energy carrier. Steel recycling and pushing the scrap rate in steel production is the first and most effective measure to reduce CO_2 emissions. But to meet future quantity demands, iron ore-based steelmaking will still be required to a wide extent. Therefore, direct reduction, today done mainly with natural gas, in future with hydrogen will gain importance.

In **Figure 1** comparison of integrated route, which is still the dominant route today, and a future green production route using H_2-based Direct Reduction (DR) followed by a two-step process employing a Smelter and a Basic Oxygen Furnace (BOF) is shown. The comparison reveals that the transition to green steel production requires a complete change in the energies consumed; while the integrated route is using enormous amounts of carbon carriers (typically 400–700kg of carbon carrier per ton hot metal), significant electrical energy is required for the green route. The biggest share of that electrical energy is required for hydrogen production. Depending on the electrolysis technology and the direct reduction processes (e.g., with or without electrical heating) 3400–3900kWh per ton of DRI need to be considered. Total CO_2 emissions of such green production route therefore heavily depend on the carbon intensity of the electrical grid (g of CO_2 per kWh).

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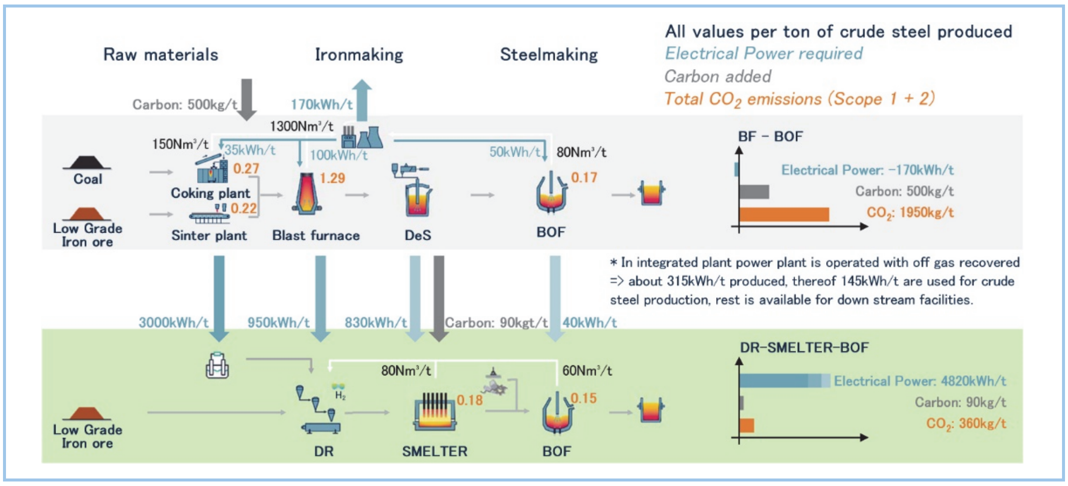

Figure 1 Integrated steelmaking route – the dominant route today – compared to future steelmaking using hydrogen-based direct reduction followed by a two-step process employing a Smelter and a BOF

2. Two-step process

While today mainly shaft process is used to reduce iron ore pellets to direct reduced iron (DRI) followed by an electric arc furnace for melting, we will see a wider variety of options for direct reduction in future, such as fluidized beds for sinter feed (HyREX) or ultra-fines (HYFOR). For high-grade iron ores with low gangue content, the slag amount during melting is low, hence the EAF is the ideal aggregate for processing. For lower-grade ores with high gangue content, a two-step process combining a Smelter with a BOF converter is required (1), (2).

The Smelter is an electrically heated furnace with main power input via resistance heating and brush arcing and due to its closed and sealed design, it has a reducing atmosphere inside. In the Smelter, the hot direct reduced material is melted, final reduction is done, and metal and slag are separated. The slag tapped from this furnace is similar to blast furnace slag and can be used after granulation in the cement industry. The metal is similar to hot metal from blast furnace and is sent to the BOF for refining. The Smelter is less sensitive to low metallization of the DRI as it is operating in reducing conditions and can handle well the final reduction. This allows an overall process optimization of DR plant and Smelter towards e.g. maximum productivity, lowest CO_2 emissions or lowest OPEX.

While the availability of high-grade iron ores that fit EAF requirements is limited, a much wider range of ore grades can be processed with the Smelter (**Figure 2** (3)). Limited availability of high-grade iron ores combined with increasing demand triggered by the numerous new DR-EAF plants under realization will push the price premium for high-grade iron ores further and boost the business potential of the Smelter.

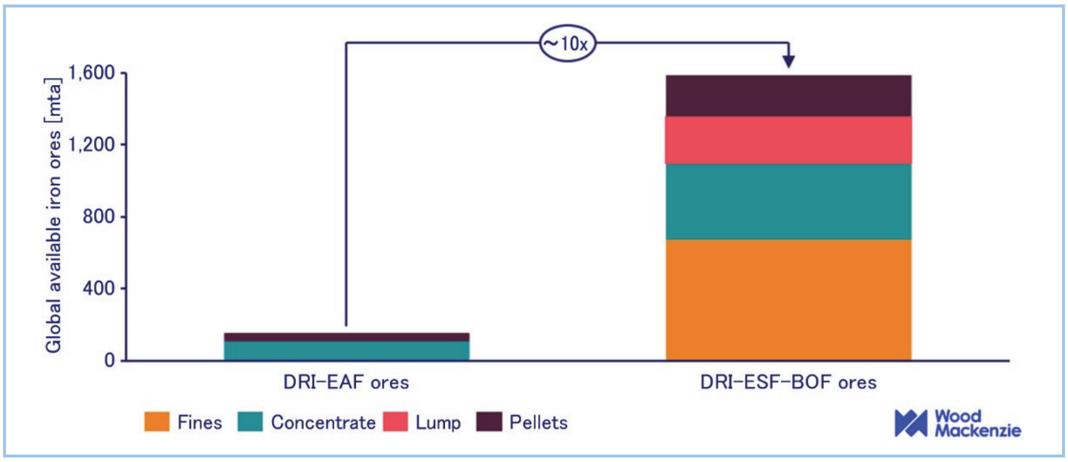

Figure 2 Global availability of iron ore suitable for DRI–EAF route and for two-step process using DRI–Smelter (ESF)–BOF route (3)

In order to prove the economics of the newly proposed two-step process, total cost of crude steel production is calculated for high- and low-grade iron ore for both process routes. The results, **Figure 3**, show that for the one-step process using an EAF the operating costs such as electricity, fluxes are much higher if low-grade ore is used. Hence, total costs are higher for low-grade ore even though the low-grade ore is much cheaper than high-grade ore. For the two-step process operating costs for both process steps do not increase that much with increasing iron ore grade and consequently the lower costs for lower-grade material dominate the price trend resulting in lower total costs if lower-grade iron ore is used. The intersection of the total cost curves shows that higher-grade ores fit better to EAF operation while lower-grade ores are better processed in the two-step process using Smelter and BOF. A more detailed analysis also evaluating the option for further beneficiation of iron ores came to similar results confirming the economic advantage of the two-step process (4).

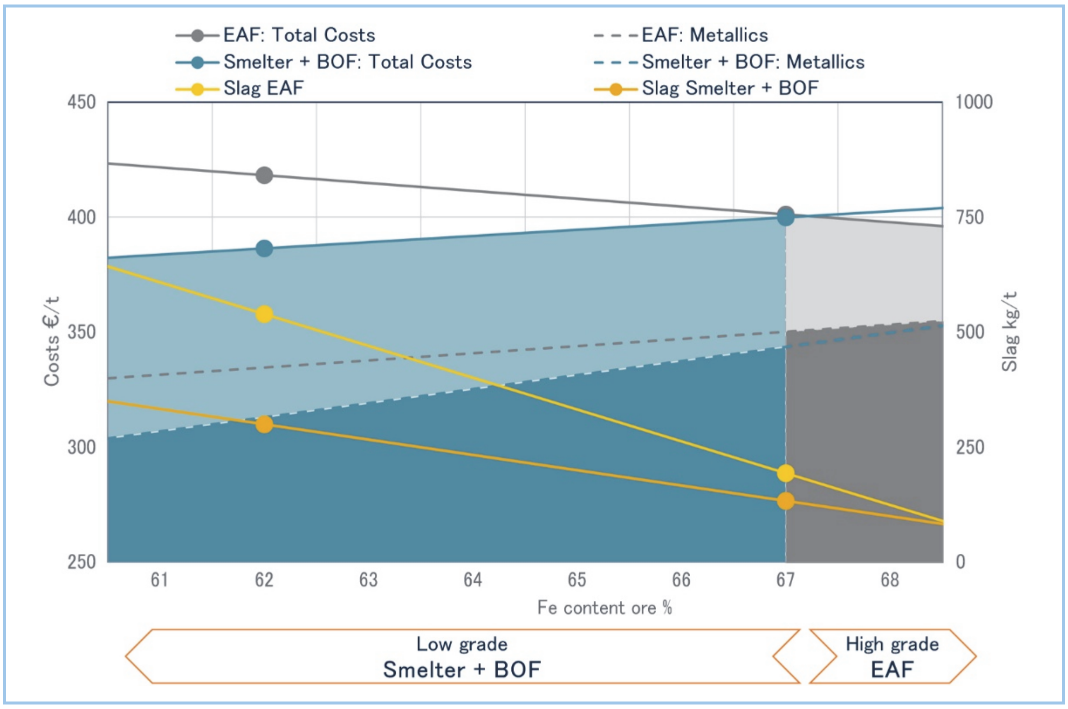

Figure 3 Comparison of total costs for crude steel produced via two-step process employing Smelter + BOF and EAF as a function of iron ore grade (Cost base: DRI 247€/ - 300€/t, Electricity 80€/MWh)

3. Smelter process principles

Due to the closed and sealed design of the Smelter, a reducing atmosphere is maintained in the furnace ensuring high yield of the carbon added, avoids reoxidation of the hot DRI feed into the furnace, and generation of a CO-rich off-gas that can be used in the process (e.g., as heating or reducing gas in the DR process). The metal produced in the Smelter is similar to hot metal from blast furnace. The carbon content can be adjusted by the carbon additions with target values depending on BOF requirements; typical values are around 3.5%. Si content will be slightly lower than BF values due to lower reduction power in the Smelter. These changes in hot metal chemistry result in a slight reduction in scrap rate in BOF operations if no countermeasures such as Dual-Flow-Post-Combustion lances, scrap preheating lances, or combined blowing converters are taken. The slag from the Smelter is similar to BF slag, needs to fit the refractory concept, and can be adjusted to the cement industry requirements in a wide range.

The Smelter is continuously operated; hence, power input and material feeding are running continuously; tapping of metal and slag from the large hot heel is done periodically by drilling and gunning. The slag has reasonable electrical resistance; hence resistance heating of the slag is possible, but thermal conductivity of the slag is rather low and consequently the energy transport and melting rate of DRI in contact with slag are limited. Hence, a brush arc will be required to boost productivity by direct melting of DRI. Electrical power input is therefore done via a combination of resistance heating and brush arcing; the maximum voltage and number of transformer taps are designed to cover full range, from pure resistance heating up to a high share of brush arcing.

The typical DRI feed to the Smelter has relatively high electrical conductivity, hence, DRI material must not be fed directly to electrodes to keep direct contact of DRI with the electrodes and current flowing via the DRI feed limited. Therefore, DRI is charged into 2 zones:

I. to areas around the electrodes where main melting takes place; due to its density, the material will float towards the electrode and is melted there by the arc and the high slag temperature (Process zone).

II. to the side walls to protect the refractory and to support the formation of a slag freeze layer (Wall zone); see **Figure 4** below for a simplified representation of the process and the process zones inside the Smelter (Process zone (orange), Wall zone (blue)). The furnace can be operated with pure resistance heating with electrodes immersed in the slag or with a mixture of brush arcing and resistance heating (Figure 4).

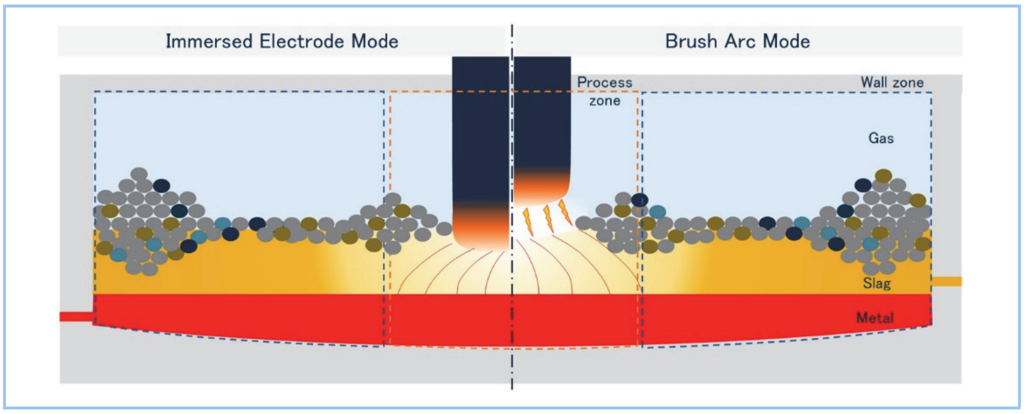

Figure 4 Simplified picture of Smelter process showing the two principal heating modes

4. Furnace design

In principle, the Smelter can be designed with round shape using 3 electrodes or rectangular shape using 6 electrodes – limits for both designs are the furnace bath area, driven by the maximum allowable hearth power density and the electrode diameter, driven by the maximum current density and the electrode consumption rate. For such new process, conservative design parameters should be used for first generation of Smelters, resulting in a maximum capacity for round furnaces of about 60MW or 0.8mta of DRI and 120MW or 1.6mta of DRI for rectangular furnaces. With such design parameters, a typical refractory lifetime of several years should be achieved. These values might increase in future based on the lessons learned from first references.

Due to its larger capacity, the rectangular furnace better fits the needs of typical integrated steel plants while round furnaces will find their application for special applications (e.g., smaller plants processing V and Ti containing ores). A full industrial plant, consisting e.g. of one large MIDREX Mega Module with an annual capacity of 2.5mta of DRI will match with two large rectangular Smelters, feeding hot DRI with inclined hot conveyors to each furnace; each with about 100MW nominal power and an annual capacity of 1.25mta of DRI.

Rectangular furnaces need solid clamping system to keep the refractory stable and prestressed during entire campaign. Primetals Technologies uses a solid frame structure for that purpose; in this frame, panels loaded by spring elements are installed to pressurize the refractory in furnace longitudinal, transversal, and vertical direction (**Figure 5**).

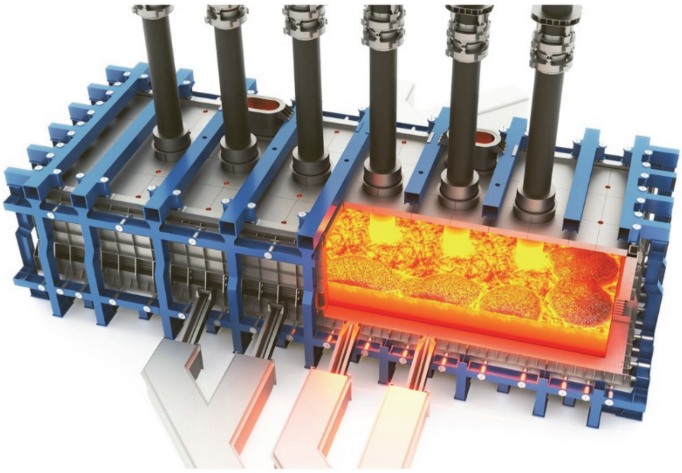

Figure 5　Structure of an industrial Smelter (about 100MW), solid steel structure is enclosing the furnace; clamping system in longitudinal, transversal, and vertical directions is pushing towards the refractory ensuring reliable clamping of the refractory

5. Experimental verification

In order to verify the process design and calculations first tests with low-grade DRI in an existing, modified electrical furnace were executed. As low-grade DRI is not yet easily available on the market, standard DRI from a natural gas based MIDREX plant was mixed with blast furnace slag to simulate the higher gangue content.

First tests were done at the 400kW furnace at ARP, Leoben, Austria beginning of 2023. This AC-furnace has an inner shell diameter of 0.9m, three 150mm electrodes, and a maximum total tapping weight of 1.1t. Due to transformer limitations, maximum voltage on secondary side was limited to 120V, allowing for intensive resistance heating but no stable arcing.

For the first test heats, a hot heel of metal and blast furnace slag was built up initially, followed by continuous charging of about 600kg of DRI together with fluxes to adjust basicity and carbon carrier for final reduction and carburization of the bath. For the latter, low-volatile anthracite was used. Two heats have been executed, furnace partly tapped in between by furnace tilting (**Figure 6** left), in each heat about 780kg of iron were produced. A thermal camera was installed at the furnace roof to monitor the area between the electrodes (Figure 6, right) – the picture shows:

1. A feed pile of DRI can be formed in the center between the electrodes to cover the bath.
2. DRI melting takes place mainly around the electrodes – DRI pellets float to this area and melt there quickly.
3. Some slag turbulence was observed around the electrodes; such turbulence is mainly caused by the CO formation during reduction and is supporting the DRI melting.

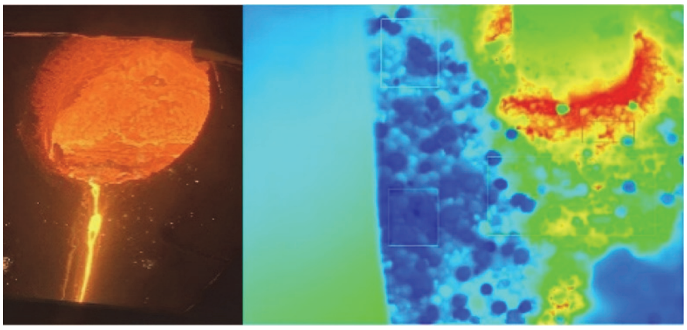

Figure 6　Melting of low-grade DRI in a modified electrical furnace Tapping of metal and slag from the furnace (left); thermal image of the area between the three electrodes showing the feed material in the center and the hot processing zone around the electrode (right)

The results of the experimental testing confirmed that process calculations and mass balance fit well. Further, the tests showed that melting of DRI in low basicity slag is possible, an average B2 basicity (C/S) of 1.05 was targeted to minimize flux consumption. Good carburization of the bath was achieved by correct charging of carbon carrier and DRI, resulting in an average value of 4.1% carbon. Finally, a low FeO level of the slag was achieved, in average 1.5% FeO – resulting in high yield of this process and confirming its advantages for low-grade iron ores.

Further tests using different carbon carriers including biochar and different forms of DRI including ultra-fine material from the HYFOR demo plant have been successfully executed recently. Results achieved are similar to values shown above.

6. Realization and upscaling

While today shaft-based direct reduction using pellets is the most mature technology, we will see a much wider range of direct reduction technologies, including solutions using fluidized bed, in the future. Primetals Technologies has wide experience for direct reduction using fluidized bed and is currently developing two new solutions: HyREX for processing of sinter feed and HYFOR for processing of ultra-fine iron ores. All these direct reduction processes need to be combined with an EAF in case of high-grade ore or Smelter in case of low-grade ore as shown in **Figure 7**. Hence, the Smelter is designed to cover full range of potential future input materials including various forms of DRI also recycled materials such as mill scale, dusts or slags (5).

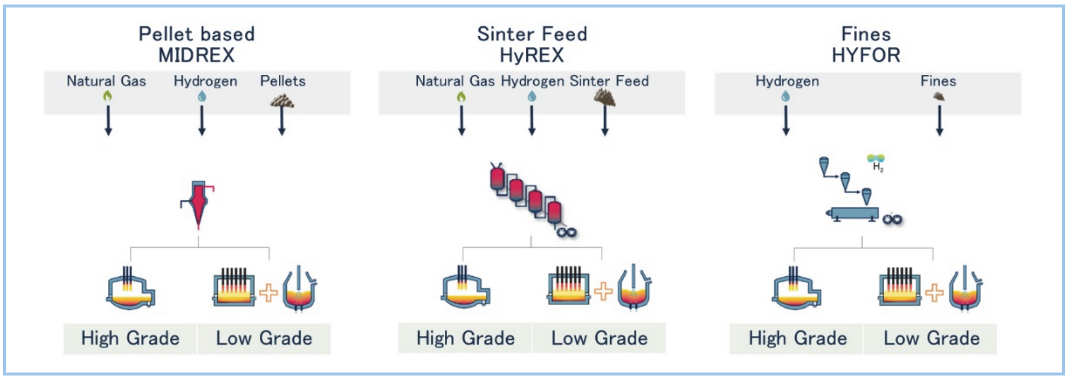

Figure 7 Future iron ore-based production routes; depending on iron ore grade (gangue content), EAF or two-step process combining Smelter with BOF will be used for processing of hot DRI

To balance risks, development costs and development time a stepwise upscaling of the process and the Smelter design is required – this can only be done with strong partners from the iron and steel industry. Primetals Technologies has partnered with voestalpine, Austria and Rio Tinto, Australia in the Hy4Smelt project to realization of a first industrial-scale prototype plant combining a HYFOR direct reduction step with a Smelter; maximum capacity of this furnace is around 3 t of iron per hour.

The next size of furnace, an Electric Smelting Furnace (ESF), with a capacity of already 30t/h and rectangular design shall be realized in cooperation with POSCO in the first HyREX project. This process combines a fluidized bed, based on proven FINEX references, with an ESF and uses sinter feed as input material.

In the final step a full industrial Smelter with capacity of 1.25mta or higher will be realized – engineering of such furnace already finished and lead customer search ongoing. Project planning including preparation for funding and permission can already start now. The last technical decisions will be made based on the lessons learned from the prototype plants, hence, start-up of full industrial furnace can be expected in 2029. **Figure 8** provides an overview about this timeline.

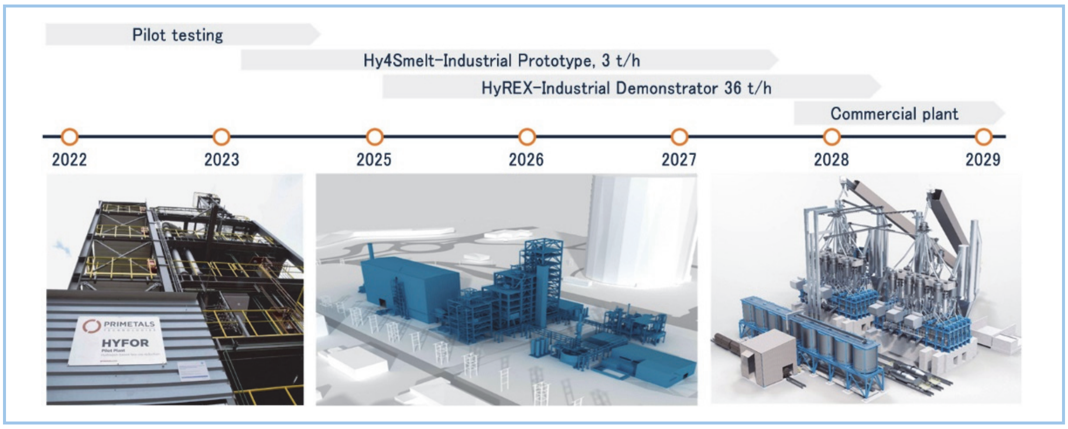

Figure 8 Roadmap for development and stepwise upscaling of the Smelter from industrial demonstration plant to full industrial furnace

7. Conclusion

This paper explores the prospects of hydrogen-based direct reduction as a pivotal strategy for mitigating CO_2 emissions in iron and steelmaking. It proposes a two-step process combining a Smelter specifically designed for processing low-grade iron ores with high gangue content into hot metal and a BOF for refining to crude steel. The Smelter operates within a sealed environment, maximizing iron and carbon yield and preventing reoxidation of hot direct reduced iron (DRI). Process calculations combined with production cost evaluation clearly show the economic advantage of the proposed two-step process for processing of low-grade DRI, verified through rigorous testing. Based on these theoretical and experimental results, a roadmap for implementation and upscaling was developed and implemented and underpinned by strategic partnerships with industry leaders. This roadmap aims to culminate in the operation of the first Smelter by 2027 followed by full industrial operation in 2029, thereby advancing the transition towards sustainable iron and steel production methodologies.

MIDREX is a registered trademark of Kobe Steel, Ltd.
HyREX is a registered trademark of POSCO Co., Ltd.
HYFOR is a registered trademark of Primetals Technologies Austria GmbH in Austria.

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