ENERGIRON® Direct Reduction Technology Contribution to Solve the 21st Century Climate Challenges of the Steel Industry

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Preamble

As of today, the iron and steel industry accounts for about 7% of global carbon dioxide (CO_2) emissions, with about 90% of these emissions from the coal-based steelmaking route.

Most countries have already committed to and climate neutrality by 2050 (compared to 1990 levels), which will require worldwide efforts, specifically for the steelmaking industry involving the dramatic shifting from coal-based to gas/electrical-based steelmaking. This will be possible through the production of Direct Reduced Iron (DRI) using natural gas (NG), as starting step, to be progressively replaced by Green Hydrogen (H_2) as ultimate target, as primary energy source for ironmaking.

Reduction of CO_2 emissions through NG and Hydrogen based DRI.

As per 2022 steel production data and our estimates of CO_2 emissions by steelmaking route, from total crude steel production of 1.885 Mt, the integrated blast furnace-basic oxygen furnace (BF-BOF) route represents about 71% of world steel production, contributing with 90% of CO_2 emissions of the steel sector while the gas-based direct reduction plant-electric arc furnace (DRP-EAF) scheme with above 5% of steel production accounts for only ~3% CO_2 emissions.

Natural gas based DRP facilities already contribute to a significant reduction of CO_2 emissions. In general, just based on the use of coal in the BF-BOF route as compared with NG in the case of the DRP-EAF route,

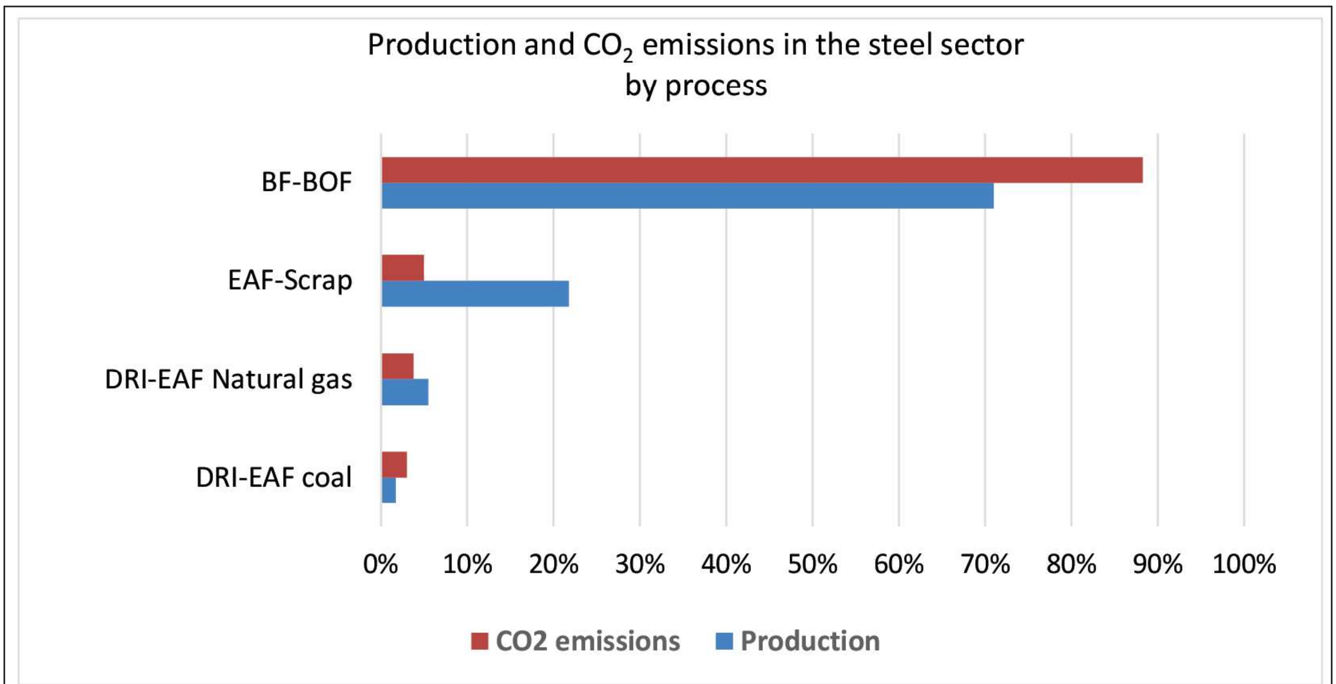

Fig. 1: Steel production and CO_2 emissions by production route

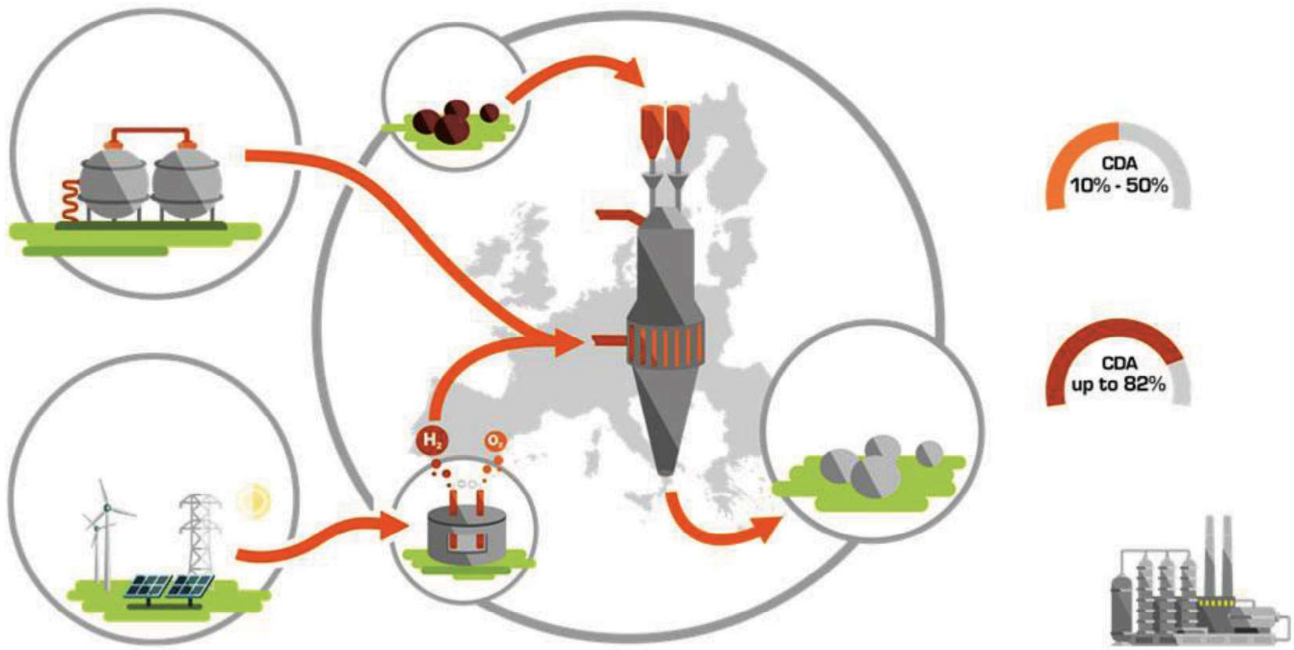

Fig. 2: SALCOS initiative in Salzgitter Flachstahl GmbH

by basic carbon material balance, the DRP-EAF route emits 40% - 60% less CO_2, depending mainly on CCU/CCS capabilities and on plant location due to carbon intensity of electricity ($kgCO_2e/kWh$), as compared to the BF-BOF route.

At present time, and based on proven and available ironmaking technologies, the pathway to follow for achieving carbon neutral steelmaking is the production of DRI with Green Hydrogen.

While ENERGIRON® process (the DRI technology jointly developed by Tenova and Danieli), with NG, typically operates with H_2/CO of 4-5 with up to ~70%H_2 vol., recent cases such as HBZX DRP in the province of Hebei, China has proven that ENERGIRON® technology is already capable to manage at industrial scale an even greater content of hydrogen in the process gas, which will further increase the emission-cut by more than 70%. Moreover, the HBIS Group have won the WSA Award for "Excellence in low-carbon production" in 2023 thanks to unique coke oven gas zero-reforming DRI process combined with EAF.

The transition towards green steel production by means of hydrogen usage is inevitable as for today, considering the available and proven ironmaking technologies. In this context, the ENERGIRON® DR technology has inherently a wide range of hydrogen usage from 0% (where only natural gas is fed as total energy) up to 100% (where only hydrogen is used for both process and fuel) with the possibility to operate the DR plant in a reversible and smooth mode. This has been already proven in demonstration campaigns at Ternium facilities and at Hybrit. Besides the fact that in case of NG the process includes an inherent selective CO_2 removal as part of the scheme, ready for CCU/CCS, the technology offers a high flexibility for the seamless and cost-effective progressive transition from NG to H_2 or direct and energy efficient (gas and power) use of H_2 as full replacement of NG.

Among the various projects in the pipeline, Salzgitter AG is leading the path of DRI production with hydrogen in Europe. Through its subsidiary, Salzgitter Flachstahl GmbH, the group has selected ENERGIRON® as technology supplier in their mission to reinvent the steelmaking process scheme. SALCOS® initiative is currently demonstrating the industry the most feasible approach towards BF-BOF route replacement with the DRP-EAF route. The project is currently in an advanced phase of engineering. On the other hand, µDRAL plant, also in Salzgitter Flachstahl GmbH premises, is a demonstration pilot-scale confirming the feasibility of ENERGIRON® technology for producing DRI with either natural gas or hydrogen.

In terms of CCU/CCS, the ENERGIRON® technology has always been characterized by a selective CO_2 removal system as part of its core and unique scheme. This CO_2 removal scheme technology has been proven in 14 DRP installations since 1980, decreasing further the carbon footprint by more than 60%.

Fig. 3: HERACLESS Project in TATA Ijmuiden Netherlands

TATA Steel Netherlands in IJmuiden with its project HERACLESS constitutes part of the decarbonization plan of TATA Steel Europe with a H_2-ready ENERGIRON® DRP together with a steelwork facility. The project is currently in engineering phase and is a key path for TATA Steel Netherlands towards being CO_2-neutral by 2045.

Following the same path, Vulcan Green Steel, a new established company of Jindal Steel Group, relied on ENERGIRON® for its new H_2-ready direct reduction plant in Duqm, in the Al Wusta Governorate in the Sultanate of Oman. Starting using natural gas as reducing agent with the possibility to mix it with up to 100% H_2, according to H_2 availability, the new ENERGIRON® DR plant will produce 2,5 Mtpy of HDRI to be charged to an EAF with a temperature >600°C, allowing significant

Fig. 4: Vulcan Green Steel in Duqm Oman

energy savings for the steelmaking process. The plant will also be able to produce low carbon footprint Hot Briquetted Iron (HBI) for storage or export purposes. The ENERGIRON® technology has the capability to capture CO_2 from the process and utilize it for other applications, which will further reduce the overall plant emissions and, together with the EAF, bring the green steel hub closer to achieving carbon-neutrality. The completion of the DRI Plant in Duqm site is scheduled for 2026.

Steelmaking routes to follow

Among the options for replacement of BF-BOF steelmaking, currently there are 2 main trends:

- DRP-EAF
- DRP-Melter ("OSBF") -BOF

DRI, as feedstock for EAF steel production, is based on the use of NG and/or Hydrogen as primary energy source for reduction of iron oxides. This is the current available technological pathway for replacing the BF-BOF coal-based scheme for decarbonization. Since the amount and composition of the gangue in the iron oxide may have significant impact on the operation and economics of the EAF, high-grade iron ores are required for DRI production to optimize the operating cost and/or steel quality production. In this context, the net-zero pathway for the steel sector, based on gas-based DRI production and using Green-H_2 as reducing/ energy agent, will trigger an increasing demand for higher volumes of high-grade iron ore pellets. In this respect there are various pelletizing projects under different stages of implementation worldwide to cope with forecasting demand.

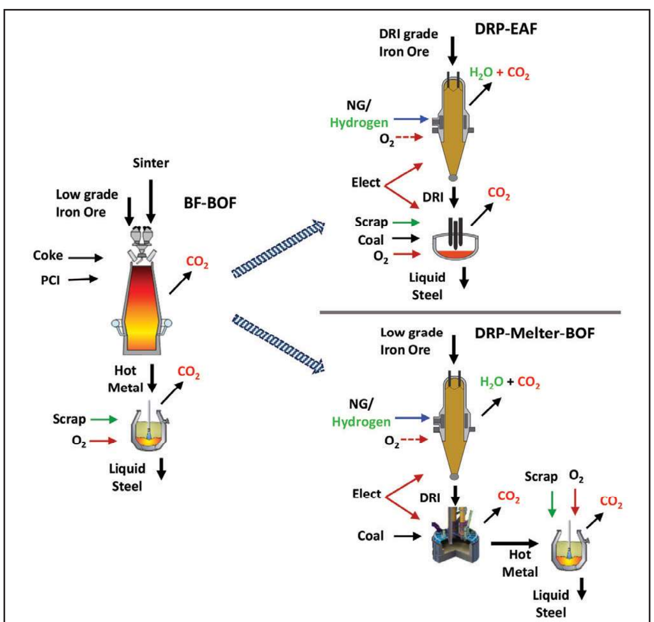

Fig. 5: The two main routes for replacement of BF/BOF integrated steel plants: DRP- EAF and DRP-Melter

An alternate and transitional approach for decarbonizing the BF-BOF installations, consists of the replacement of the ironmaking BF system by gas-based DR plant and electric melter ("OSBF" - 'Open slag bath furnace') while keeping BOF downstream steelmaking facilities in operation. The scheme comprises the DR plant for HDRI production feeding an OSBF, for production of hot metal. DRI is produced using NG and H_2, and low- grade iron ore pellets, which is fed to an OSBF to produce hot metal (as feeding material to existing BOF's), and granulated slag. For this approach, fitting the needs of integrated steelmakers in decarbonizing the integrated mill, Tenova offers the highly energy efficient iBLUE® scheme including heat recovery from off-gases as fuel in the integrated DRP process gas heater.

The main advantage of this route is the possibility of processing low grade pellets (Blast furnace type) with the resulting amount of slag, which can be converted in the OSBF into a slag that is completely like the Blast Furnace slag.

The iBLUE® therefore is a valid alternative to the blast furnace, being able to utilize almost the same raw materials and able to produce the same type of outputs (hot metal and Blast Furnace-type slag) but requires higher CAPEX in case of greenfield installations (needing an oxygen steelmaking plant).

DRP-EAF, an already traditional and proven steelmaking route.

It is expected that most of the steel to be produced worldwide from DRI will be based on the DRP-EAF route, as a well-known and proven technology in regions such as North America and MENA.

As reference, there is the pioneering path historically followed by Tenova since the 1950's, and the recent announced Pesqueria Plant for Ternium Mexico. This represents Ternium's largest investment plan to date involving around 2.2 billion USD for a DRP with integrated material handling, an EAF equipped with Consteel® and Electromagnetic Stirrer Consteerrer®, two ladle furnaces (LF), and a Fume Treatment Plant for a guaranteed total production of 2.6 Mt of high-quality steel for the automotive sector.

Increasing demand on green DRI and scrap

DRI/HBI trade is expected to increase from 7% to a maximum of 30% by 2050.

As per EU scenario, new EU-ETS regulations on CO_2 Emissions; 1)- reducing emissions 55% by 2030

Fig. 6: Ternium Pesqueria Project including a 2.1Mtpy ENERGIRON DRI Plant

and climate neutrality by 2050, 2)- phasing out free allowances for companies from 2026 until the end of 2033, 3)- additionally, tariffs on non-green steel imports, will require production of green DRI domestically or green steel and/or green DRI/HBI imports, sourcing worldwide. Similar targets are being followed by several countries worldwide.

As mentioned above, this demand shall be met by green steel produced from green DRI and scrap. Hence, companies like Arcelor Mittal have already placed their visionary strategy towards green steel transition through DRP facilities. As of today, ArcelorMittal Dofasco in Canada, consisting of 1x2.5 MTPY DRP for Hot DRI production whose objective is to replace BF/BOF operation, is currently in engineering phase. Additional clusters in Europe are expected to join the Canadian project in the short term, also with ENERGIRON® technology.

Which route to follow?

While selecting the steelmaking route to proceed with for decarbonization, the most important parameter is the CO_2 emissions factor. Currently, depending not only on direct CO_2 emissions but also on those as per Scope 2 and Scope 3, are related to several factors, including the local carbon intensity of electricity ($kgCO_2e$/kWh), iron ore and consumables sources, etc. In this regard, the following analysis is based on the following considerations:

- The selected DR technology includes capabilities for efficient and inherent CO_2 removal for CCU/CCS (ENERGIRON®), to prevent further emissions while capturing CO_2 emissions.
- When applicable (others than 100%H2 scheme), CO_2 emitted from flue gases has not been considered for CCU/CCS at this stage due to inefficient and more energy demanding (increasing CO_2 emissions).
- H_2 to process & fuel for 100% H_2 schemes.
- Location of 0.38 kg CO_2/kWh electricity intensity.
- For the DRP-Melter-BOF scheme, recovery of off-gases from the melter and used as fuel in DRP.
- Including Scope 2 (power from external sources) and Scope 3 (oxygen, iron ore pellets and other consumables) [Emissions Factors WSA], as indicative burden.
- Production of Hot DRI with 94% Mtz and, 1)- for NG: 4,6%C for melter, 3,6%C for EAF and 2)- for 100% H_2 use: 0% C.

As reference, the following indicates the scenario without any CCU/CCS in the DRP.

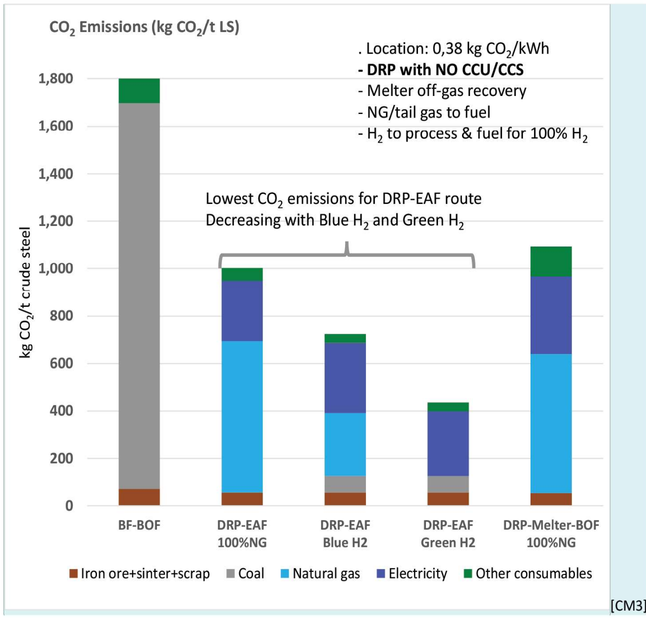

Fig. 7: Expected CO_2 emissions for different routes without CCU/CCS

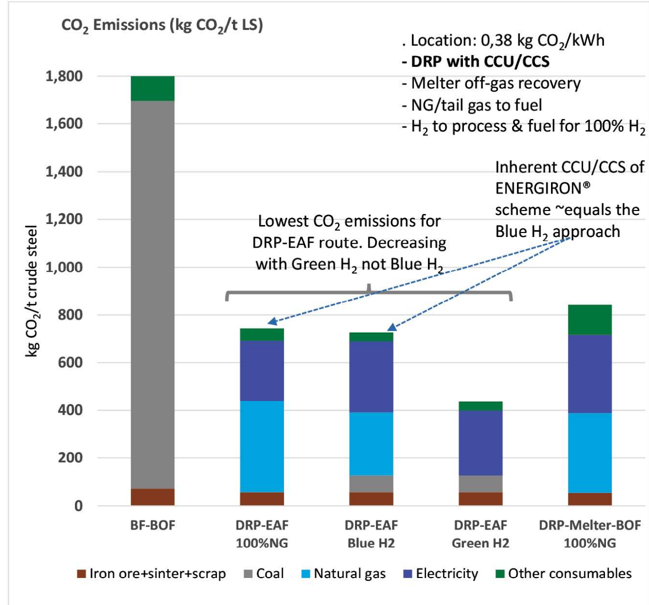

Fig. 8: Expected CO_2 emissions for different routes with CCU/CCS

On the other hand, by including inherent ENERGIRON® CCU/CCS capabilities, the results present a significant different scenario.

Based on above listed considerations, when comparing DRP-EAF with NG and Blue/Green H_2, whenever there is the possibility of ENERGIRON® technology, with inherent selective CO_2 elimination for CCU/CCS, as has been and is the case for various DR plants installations worldwide with selective CO_2 off-taking, the direct use of NG followed by Green-H_2 will be the efficient and economical approach vs. Blue H_2 in terms of CO_2 emissions. It can be noted that for ENERGIRON® iBLUE®-BOF scheme, with 90%-100%NG, as unique characteristics, there is a much-reduced need of coal addition to the melter since the DRI is already discharge with >4%C thus, optimizing operating and reducing carbon footprint in addition to inherent CCU/CCS. Moreover, the presence of a reducing environment within the OSBF promotes the reduction of the remaining FeO in the DRI pellets, thus achieving higher iron yields.

The arc mode reduces to a minimum the Nitrogen pickup in the hot metal, making the metal compatible with the typical integrated steel mill secondary metallurgy.

In any case, even with the use of Green-H_2 for steelmaking in achieving 2050 net-zero emissions, there will be limited but certain coexistence between iron and carbon. In fact, this is the nature of the steel alloy. Sources of carbon will be related to minimum coal injection in EAF, from carbonates (lime, dolo-lime), electrodes, as direct CO_2 emissions, and oxygen, scrap, and electricity (depending on carbon intensity), as indirect emissions in connection to Scope 2 and Scope 3 inputs, which only possibility for neutral carbon will be through CCU/CCS and minimizing carbon footprint respectively.

In addition to CO_2 emissions, there are other important factors to be considered while selecting the route to follow in implementing ironmaking/steelmaking projects.

- Availability and forecast of pricing of raw materials and energy for OPEX analysis (iron ore, scrap, NG, H2, electricity, etc.). Particularly, it is the case of DRI grade pellets premium vs. low grade pellets.
- The presence of existing BOF facilities vs. greenfield installations (in greenfield typically the EAF route is preferred, while in brown field integrated steel mills both EAF and OSBF routes could be viable)
- Local regulations
- Steel quality to be produced, with particular focus on secondary metallurgy requirements and processes.
- Financial support to decarbonizing projects.
- Electrical network capabilities.
- Slag disposal/off-taking and reverts from the steel mill.

- Availability for CCU/CCS solutions.
- Logistics constraints

CONCLUSIONS

Steelmakers need different alternatives for decarbonizing existing installations. Selecting the adequate path requires, among others, strategic evaluation of different solutions related to local regulations and conditions, raw materials and energy sourcing, quality of steel to be produced.

The availability of technologies to produce steel has evolved significantly in the last 5-years, some are at early stages of development while others are already mature, proven, and H_2-ready for implementation in an efficient and cost-effective manner.

Tenova believes that ironmaking/steelmaking technology providers have the important role in opening flexible options for the customers without taking a one-size-fits-all approach, as has been the case for most projects under different stages of operation and implementation.

The decision on which technology to implement is critical and complex with a myriad of factors to take into consideration and this paper only surfaced a few. Tenova sees the role of technology providers in this phase of the history of our industry, not just as the one of equipment and process providers, but rather as consultants who, with the experience grown in several different projects in a variety of locations and setups, can study with steel producers the best solution for each single case.

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