Conventional steelmaking route being subject to transformation

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Several aspects in BF ironmaking technology will become the major bottleneck and restrict its further development, even if, currently, the blast furnace (BF) process still represents the predominant technology, especially in China. In this paper Tenova S.p.A. is going to present technologies in the field of direct reduction and electric steelmaking to substitute BF/BOF via DRP and EAF plant solutions in a stepwise transformation process and shows how to achieve comprehensive utilization of each composition of raw materials. The paper will demonstrate results of BF of enhanced performance and productivity with in parallel reduced coke / PCI as well as carbon footprint utilizing DRI. Furthermore the potential usage of hydrogen as reducing agent in ENERGIRON-ZR process to replace carbon carriers, the potentials in utilizing DRI in SAF to produce high purity pig iron (HPPI) and the treatment of VTM and also capabilities of sophisticated automation and measurement packages (iBOF) to enhance performance of BOF process as a very first step in this transformation process.

KEYWORDS: DRI/HBI CHARGE INTO BF - DRI+EAF AS BOF/BF SUBSTITUTE - H2 AS REDUCING GAS FOR DRP - IBOF PROCESS CONTROL - OXYGEN LANCE DESIGN - DRI TO PRODUCE HPPI AND TREAT VTM, CARBON FOOTPRINT – HYDROGEN - FLEXIBILITY

INTRODUCTION: CHALLENGES FOR IRON AND STEELMAKERS

Iron- and steel makers are facing an ongoing process of transformation. Rapidly changing conditions on political and social level, approval procedures for new installations and their potential impact on public perception, raw material quality and availability, different energy sources on changing price levels, stricter environmental regulations and greenhouse gas emission reduction targets, the upcoming hydrogen era and in general difficult to predict market conditions are topics steelmakers has to take care of.

Overcapacities from China and its MES status and the not finally regulated and limited to Europe stricter CO_2 emission policy are additional growing threats the European iron- and steel industry has to deal with.

Also Europe is facing significant structural overcapacities. But the European steel industry is doing a lot to optimize processes in terms of utilizing BF gas and COG in own power plants, using preheating technologies to enhance energy efficiency squeezing out their plants to secure profitability and economic benefits. That means European steel industry is on a high level in efficiency and on the limit in terms of technical optimization with the existing plant portfolio.

The EU wants to cut its CO_2 emissions by 40 % the next years and the Iron and Steel industry is one of the largest producers of CO_2 emissions. These are facts. From a political perspective, there will be fewer allowances in the next years and they will be expensive, means the EU sets the permissible emissions firmly and reducing them further annually. In detail: The quantity of allowances should be reduced from year 2021 annually by 2,2%.

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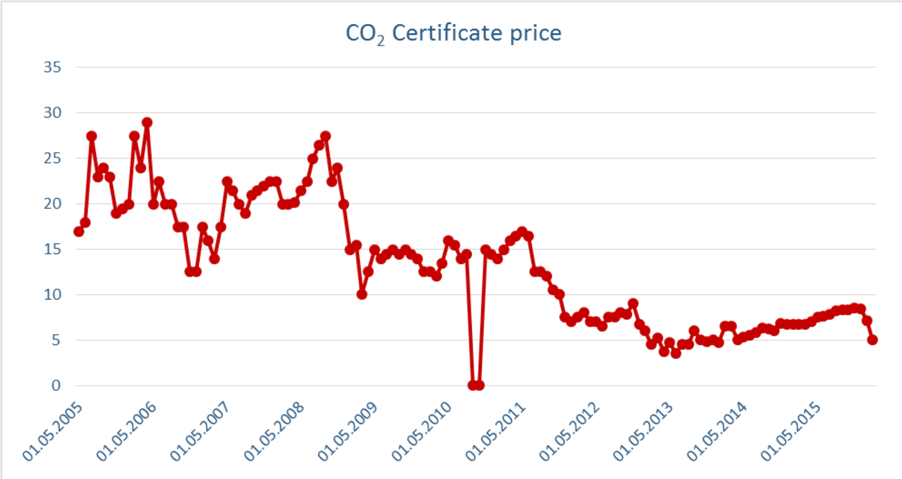

Fig. 1 – CO_2 certificate price over years

But the European steel industry is in a global competition with lower wages and less strict environmental regulations and is additionally facing the emission trading system and related laws and regulations. From that point of view, we are far away from a fair global competition. For the time being the price for CO_2 certificates are very low (Figure 1).

Studies investigated different possible scenarios with higher prices for energy, fuels and certificates [1]. Three different scenarios were considered: A Baseline Scenario (BS) which dealt with the estimated projection in production and demand, scrap availability and energy resources and CO_2 prices is adhered to (based on a study of 2009), an Alternative Scenario 1 (AS1) analyzing the influence of the increase of fuel prices in the Iron & Steel Industry and an Alternative Scenario 2 (AS2) which examines the effect of the variations of the price of CO_2 emissions. Target was to explore strategic opportunities for steelmakers in the current climate and how innovation in raw materials, energy distribution and transformation as well as product quality can create opportunities for business.

The result can be summarized as follows: No matter which scenario occurs; it is necessary to install new technologies! To reduce the carbon footprint as expected by the European laws and regulations requires an investment in new carbon footprint reducing technologies, and this is without alternative.

Potential technologies for decarburization are coke dry quenching, BOF waste heat and gas recovery, continuous casting, scrap pre-heating solutions, oxygen-fuel burners, top gas recovery turbines, CO_2 capture and use for fuels/chemical production and direct reduction technologies as well as latest analyzing and measurement technologies. Most of them are already implemented in melt shops and integrated plants. But this will not be enough to meet future needs, to fulfill todays and future environmental regulations and to cope with upcoming threats. What the European steel industry and especially integrated plants need is a paradigm change, a continuous and stepwise transformation process to remain competitive.

TENOVA APPROACH: A STEPWISE TRANSFORMATION PROCESS INTO SUSTAINABLE, ENVIRONMENTAL-FRIENDLY AND ECONOMIC STEEL PRODUCTION

iBOF technology – a step ahead in basic oxygen furnace processing

Tenova's iBOF® "intelligent Basic Oxygen Furnace" is a modular technology developed by Tenova Goodfellow Inc.- in Canada - to reduce GHG emissions while improving yield, productivity and scrap-melting capability cutting operating costs. It includes NextGen® multipoint hybrid laser/extractive off-gas analysis hardware for improved process control & safety, robust mass & energy balance endpoint process models, intelligent slop mitigation technology and automatic tapping control technology for improved safety, reduced slag carryover & minimum ladle reversion. This package represents the first of further steps - means optimizing existing plant capacity – and provides features to enhance energy efficiency, process predictability and off gas treatment.

Module 1 - C&T Endpoint Detection - uses a combination of Tenova's newly launched multipoint hybrid NextGen® off-gas analysis technology together with proprietary process models and sensors. Module 1 significantly improves carbon and temperature end-point control and thereby lowers conversion costs (reduced tap alloys, O2, refractory & consumables), increases productivity (fewer reblows) and increases yield (lower FeO). Module 2 - Early Warning Slop Detection: uses advanced sensors and proprietary software to continuously monitor changes in lance vibration. Tenova Goodfellow's - proprietary software interprets the signals in real-time to obtain a 20-40 second advance warning of the onset of a slop as well as an indication of slop severity the effects of a slop event. Module 3 - Optimized Post Combustion - enhances "in-BOF" post combustion for increased scrap melting by using a combination of proven full spectrum off-gas analysis technology together with dual flow lance technology. Module 4 - Automated Tapping Control - provides control technology for operator assist or for fully automated tapping to improve safety, minimize slag carry-over and reduce operating cost. With over 90 installations worldwide, EFSOP® extractive off-gas technology is the world leader in real-time off-gas analysis.

The ENERGIRON-ZR process and its features to meet future needs

Developed in pilot plant in the 1980's and successfully started at full industrial operation in 1998, the ENERGIRON Process scheme (Figure 2), now jointly developed by Tenova HYL and Danieli & C. Officine Meccaniche S.p.A., is a major step in reducing the size and improving the efficiency of direct reduction plants. Reducing gases are generated by in-situ reforming of hydrocarbons within the reduction reactor, feeding natural gas as make-up to the reducing gas circuit and injecting oxygen at the inlet of the reactor [2]. The basic ZR scheme permits not only the direct use of natural gas (NG) but same basic process scheme is used regardless of the reducing gas source, such as reformed gas from an external reformer, syngas from coal gasification, pet coke and similar fossil fuels, hydrogen, and coke-oven gas, among others, depending on availability. Operating conditions of the ZR process are characterized by high temperature (~1080°C) and high pressure (6-8 bar A at top gas). The elevated pressure allows a high productivity of about 10 t/h x m² and low reducing gas velocities of about 2 m/sec, as compared to lower operating pressure processes for which the gas velocities are >5 m/sec. The lower gas velocities reduce dust losses through top gas carry-over, thus lowering the overall iron ore consumption, which is reflected in overall operating costs. A distinct advantage of this process scheme without an integrated reformer is the wider flexibility for DRI carburization while using NG.

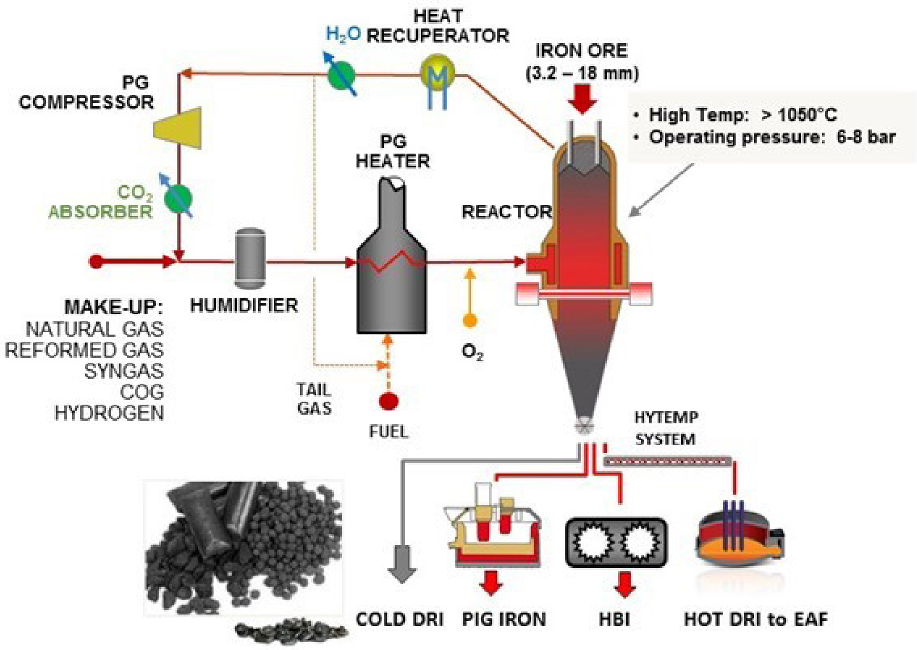

Fig. 2 – ENERGIRON ZR Process scheme

As indicated in Fig. 2, the ENERGIRON ZR scheme can produce cold DRI (CDRI), hot DRI (HDRI) which can be directly fed to: 1) Hytemp System for transport and direct feeding to an adjacent EAF, 2) to briquetting presses for production of HBI and 3) to a smelting furnace (designed by Tenova) for production of pig iron. The latter is a breakthrough approach for production of pig iron using NG as reducing agent, decreasing to ~50% the carbon footprint as compared to the conventional coal-based technologies (BF, Corex, etc.). One of the key features of this technology is the inherent selective elimination of both by-products of the reduction process: H2O and CO_2. As indicated in Figure 3, about 62% of total carbon input to the process and fuel is selectively removed via a CO_2 amines-based system. This CO_2 can be and is being commercialized as valuable by-product for different industries as Carbon Capture and Use (CCU) approach. As current CCU references, some examples for CO_2 usage are: Ternium DRI plant (Monterrey, Mexico), Ternium DRI plant (Puebla, Mexico) to Praxair, PTKS DRI plant (Indonesia), PSSB DRI plant (Malaysia), CO2 used in food and beverages industry; JSW Salav (India). HBI/DRI plants of India are providing pure CO_2 to Air Liquid for production of dry ice; ENERGIRON DRI plants (Emirates Steel, Abu Dhabi) CO_2 (about 25% of total amount) will be compressed and then pumped into oil wells for enhanced oil recovery (EOR) operations.

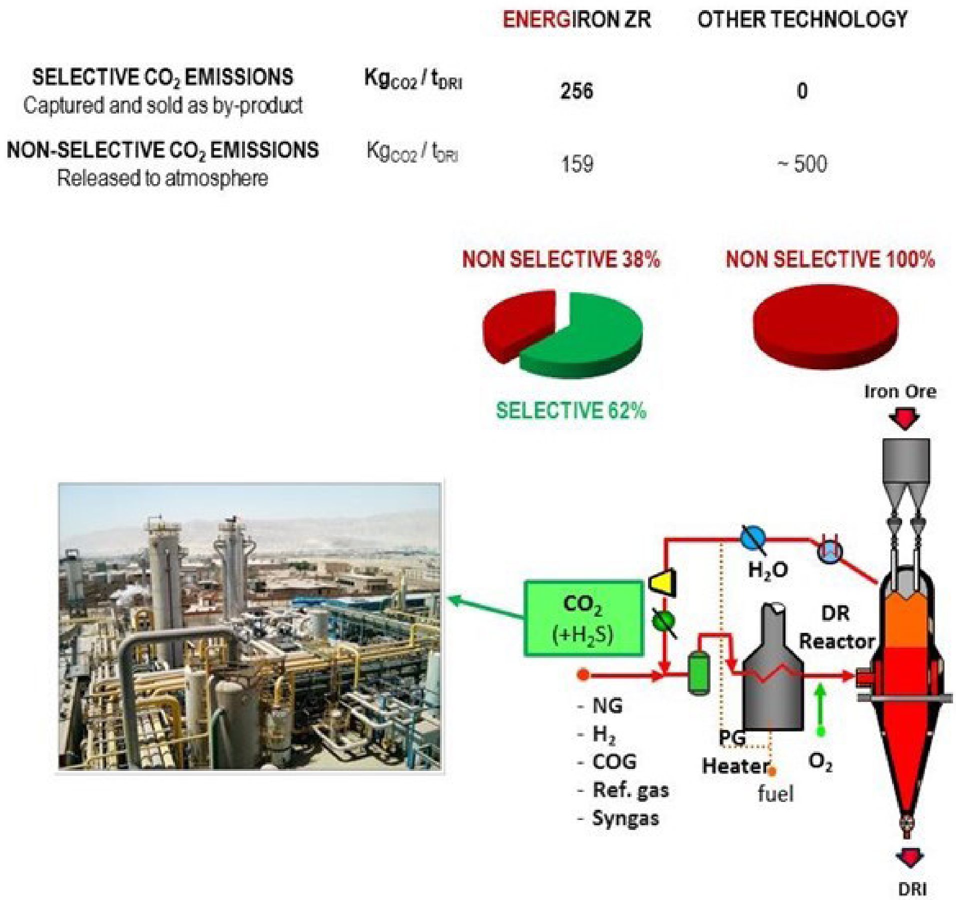

Fig. 3 – Selective CO_2 removal in ENERGIRON ZR process

Advantages of utilizing High-C DRI in BF operations

The use of direct reduced iron (DRI) or hot briquetted iron (HBI) as metallic charge to BF allows a significant reduction of fossil fuels specific consumption. Several steelworks have already used DRI/HBI in the BF during the last decades and have reported the results. In general, each 10% of burden metallization in the mix charge, the coke rate can be decreased to 6% to 7% while the productivity can be increased by 7% to 8%. All the reported results in Figure 3 are based on the use of traditional DRI/HBI which implies carbon levels not higher than 2.0%C. A further decrease of the PCI/coke consumption and increase of the BF productivity can be reached whenever High-C DRI/HBI (≥4.0%C) is used instead of standard DRI/HBI (<2.0%C). In the ENERGIRON DRI, more than 90% of the carbon contained in the High-C DRI is in the form of iron carbide (Fe3C). In this respect, the following additional benefits are expected when using High-C DRI/HBI to the BF:

• The secondary reduction of the remaining wustite (FeO) in DRI with the carbon. This reduction reaction generates CO gas which can also reduce the iron ore around the DRI, improving furnace efficiency and decreasing PCI/coke requirements. This effect is limited with the traditional DRI/HBI with lower carbon content. Refer to Figure 4 for the effect of the High-C DRI in the BF.

• The additional energy provided by the excess of carbon in the DRI.

According to this analysis, the PCI/coke rate can be decreased down to 8% to 9% while the productivity can be increased up to 9% to 10% for each 10% of metallized burden in the feed charge if using High-C DRI/HBI. Considering a DRI/HBI charge for a typical BF-BOF installation of about 35% burden metallization, power as CO_2-neutral, and depending on DR Plant location (abroad or on-site), the use of High-C DRI/HBI reduces the CO_2 Emissions in 26,3% or 17,6% respectively, depending on DRP location.

High-C DRI + OSBF/EAF/SAF – a solution for production of NG-based pig iron

The conventional method for production of pig iron is mainly BF, based on the use of coal; coke and PCI. Other route is based on smelters like Corex, also based on coal. The novel approach by Tenova for production of pig iron, using NG as primary reductant, is based on Tenova's OSBF Technology or Tenova EAF/SAF combined with the propriety NG based ENERGIRON-ZR process, providing a distinct advantage in the production of high purity pig iron (HPPI). Furthermore, the carbon footprint and the overall electrical energy consumption could be reduced by utilizing our hot charge feed system from the reactor into the OSBF or EAF/SAFThe reduction of carbon footprint for production of pig iron by 50% is significant.

Hydrogen in ENERGIRON-ZR process

As observed in Figure 1 above, the ZR process scheme configuration is the same for any application, regardless of whether using natural gas (CH4), hydrogen (H2), reformed gas from external steam/NG reformer, syngas from coal gasifiers, or COG. This provides a significant flexibility as compared to other DR technology. For the HYL/ENERGIRON DR technology, there are some characteristics which makes this process scheme the most suitable for H2 use; i.e.:

• The ZR process scheme is "natively" suitable for any reducing gas make-up, specifically H2.

• H2 make-up directly replaces NG to the process.

• High operating pressure to better handle the lightest and more diffusible compound in nature.

• Vast experience with high H2 concentration (~70% volume) in HYL/ENERGIRON plants. Since the 1950's, the HYL/ENERGIRON plants, using reformed gas as source of reducing gas, includes a conventional steam/NG reformer.

• Extensive pilot plant campaign in Monterrey during the 1990's, using ≥ 90% H2 as reducing gas.

From the thermodynamic point of view, H2 reduces iron oxide easily than CO, as per change of Gibbs free energy @ 845°C. On the other hand, iron ore reduction with only H2 is a highly endothermic reaction, favored at high temperatures and requiring high H2 concentrations at lower temperatures. Reduction with CO is a highly exothermic reaction, favored at low temperatures taking place at lower CO concentrations.

$$Fe_2O_3 + 3H_2 \Rightarrow 2Fe^\circ + 3H_2O \quad \Delta G^\circ \text{ @ } 1118°K: -9.201 \text{ kJ/kg mol } H_2$$
$$3Fe_2O_3 + 2CO \Rightarrow 2Fe^\circ + 3CO_2 \quad \Delta G^\circ \text{ @ } 1118°K: -8.222 \text{ kJ/kg mol CO}$$

$$Fe_2O_3 + 3H_2 \Rightarrow 2Fe^\circ + 3H_2O \quad \Delta H_{rxn} \text{ @ } 1118°K: +21.763 \text{ kJ/kg mol } H_2$$
$$3Fe_2O_3 + 2CO \Rightarrow 2Fe^\circ + 3CO_2 \quad \Delta H_{rxn} \text{ @ } 1118°K: -12.081 \text{ kJ/kg mol CO}$$

However, thermodynamic data do not provide information on the rate at which the reduction reactions would take place. This depends on the reactions kinetics which is determined by the prevailing process conditions. These process parameters can be only determined by experimental testing. Kinetically, iron ore reduction with H2 is >4 times faster as compared to CO and, because of the highly endothermic behavior, requires higher reducing gas temperature.The off line reformer used for DR plants is based standard technology with hundreds of references in DR and hydrogen plants; there are more than 40 HYL/ENERGIRON plants having used this type of NG reformers. Typical operation parameters of the DRP's with reformer are as follows:

Parameter related to H_2	ENERGIRON	Other DR technology
H_2O/C ratio in Reformer	2.0 – 2.5	1.5
H_2/CO ratio in reducing gas	4 - 5	1.7
$\%H_2$ to reactor (% vol.)	~70%	~55%

In addition to the vast industrial experience using H2, in the 1990's, Tenova HYL carried out extensive tests at pilot plant (Figure 3) with ≥ 90% H2; producing H2 from reformed gas from the industrial DR plant after shifting and CO2 removal. These tests provided all necessary information to define:

• Process and design parameters mainly related to optimized flow-temperature correlation.

• DRI quality in terms of metallization and carbon content, which is less than 1% above 75% H2.

• Optimization of operating pressure, reactor L/D ratio, solids residence time, to consistently achieve the DRI quality, determination of fluidization factor (*ƒ*) to ensuring proper gas velocities and distribution through the solids bed, among others for the proper gas distribution and design of the scheme for H2 utilization.

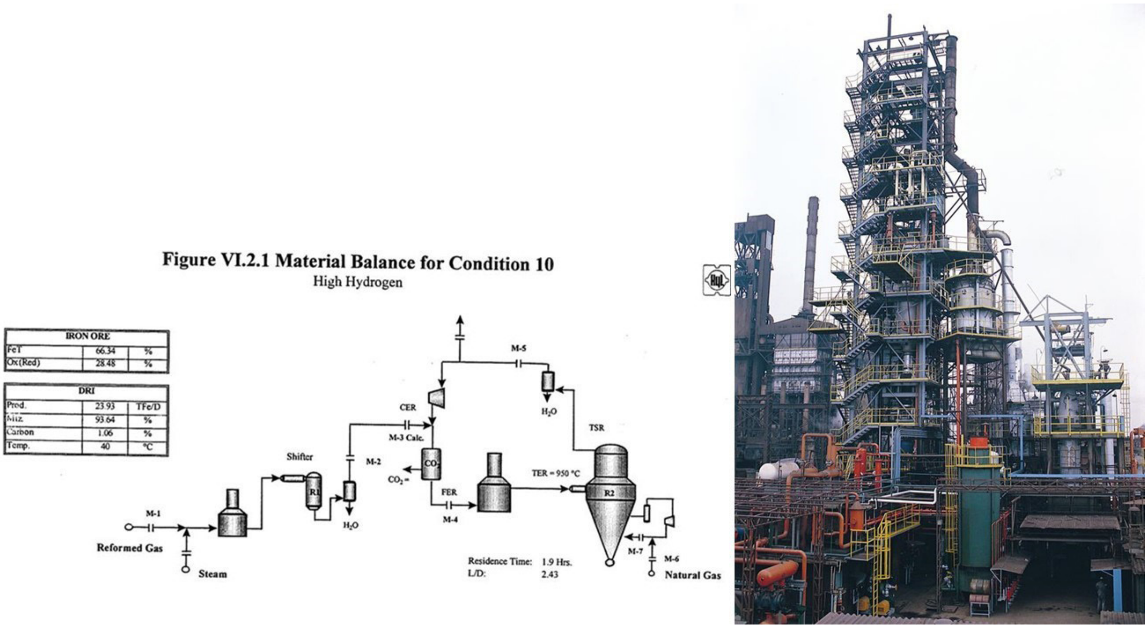

Fig. 4 – HYL Pilot Plant tests campaigns with ≥90% H2

Additional benefits of the ENERGIRON ZR technology for the direct use of H2 is related to the high operating pressure (6-8 bar). H2 is the most diffusible gas in nature thus, tight sealing is required to prevent any leak. In the HYL/ENERGIRON DR plants, the high operating pressure is managed through the use of mechanical sealing for pressurization/de pressurization from atmosphere. Mechanical sealing allows higher P due to friable ores and/or additional fines, preventing any gas leak/air intake. For this case, any additional P is simply handled by the compressor instead of lower gas flow and/or decreasing production rate.

On the other hand, the gas velocity of the gas inside any moving bed reduction shaft has the following functionality:

$$V_G = V_{mf} * f = k * \frac{F_{G(act)} * F_S * (M * T)^{1/2}}{D_i^2 * P^{1/2}}$$

where:

f is the fluidization factor. f shall NOT exceed 1,0

V_{mf} is the velocity of minimum fluidization; i.e. gas velocity at which the solids flow is suspended

k is a function of bed porosity, gas density and viscosity, solids density, particle size

$F_{G(act)}$ = Specific reducing gas flowrate (actual cond.)

Fs = Production rate

M = Gas molecular weight

T = Reducing Temperature at reactor inlet

P = Operating pressure

Di = Reactor internal diameter

It can be easily noted that a high operating pressure shaft allows better flexibility for a small diameter (Di), to comply with fluidization, and larger height (L), for a better gas distribution. In terms of energy consumption, the impact of H2, as compared to NG is indicated in Figure 5, crediting the %C in the DRI.

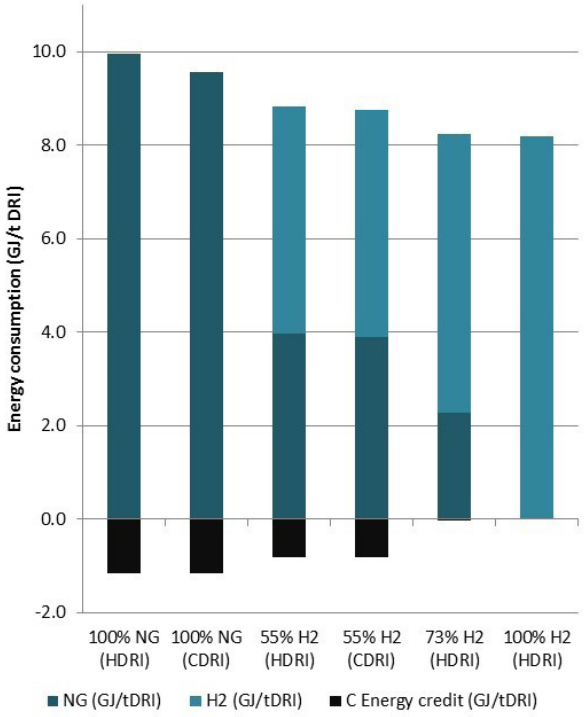

Fig. 5 – Comparative energy consumption figures with H2 use for Direct Reduction in ENERGIRON plants

As summary and based on the above facts, ENERGIRON is the only available DR technology fitted for the proven, efficient and reliable use of H2. For this industrial application, to comply with the CO_2 emissions targets, H2 shall be generated by high efficiency electrolyzers, like the reversible high-temperature electrolyzer (HTE) type, powered by renewable energy source; i.e., eolic, solar PV.

A stepwise replacement of BF/BOF plant capacity by DRP/EAF facilities - CDA

The ENERGIRON-ZR process with its characteristics and features such as selective CO_2 removal, hydrogen utilization and High-C DRI production provides already the technology to meet future challenges. The SALCOS (Salzgitter Low CO2 Steelmaking) project, a study initiated by Salzgitter AG together with Tenova and Fraunhofer-Gesellschaft (FhG) in 2015, had to analyze the capabilities of already existing technologies to reduce greenhouse gas emissions, to investigate implications on integrated steel works and so to demonstrate the possibility for significant contribution to carbon footprint reduction. The advantage of SALCOS approach and the incorporation of ENERGIRON-ZR/HYL technology is the possibility to go directly for a large industrial-scale pilot plant avoiding the necessity for laboratory scale studies. Especially taking into consideration visible changes of climate, the changed perception of global society as well as the defined climate targets for 2050, this concept provides the possibility to act now. The general approach behind is, in contrast to CO2 usage (CCU) or disposal (CCS) concepts, the avoidance of carbon carriers and the usage of hydrogen instead. Hydrogen can replace carbon in iron ore reduction processes, leading to the final formation of water (H2O) rather than CO_2. Additionally, process heat for steelmaking may be supplied by electrical energy instead by carbon. Based on these simple facts Salzgitter defined the term CDA – "Carbon Direct Avoidance" in order to underline the difference to already existing and not consequent utilized and well thought out concepts. Avoidance of CO_2 formation directly in steelmaking processes is more sustainable and also energetically more useful than any further utilization. As one of the major results the SALCOS study could demonstrate the possibility to follow stricter CO_2 reduction targets in Europe after 2030 by realizing a stepwise transformation process of integrated iron and steel works towards direct reduction and electrical energy based steelmaking processes. This transformation process, realized in subsequent steps, reduces the environmental impact in terms of CO_2 emissions up to around 95% depending on framework conditions. As a first step, an additional gas-based direct reduction plant (DRP) (ENERGIRON ZR process) has to be realized at the integrated site in Salzgitter. The produced high carbon DRI (HC-DRI) from this plant is utilized in existing BF's to enhance productivity and to reduce coke as well as PCI in parallel. This step already reduces the carbon footprint of steel production of Salzgitter by around 10%, as natural gas used for reduction has a certain amount of hydrogen content. With electrolysis on an industrial scale hydrogen can further replace natural gas and so carbon carriers partly. In case of operating electrolyzers with power from renewable resources only, the overall CO2 emissions can be reduced up to 18%. Precondition is the availability of electrolyzes capacities on a very large scale (largest capacity ever realized) to provide an appropriate gas mixture (natural gas/hydrogen). In conjunction with the flexibility of the DR plant / ENERGIRON ZR process utilizing different reducing gases in varying ratios in full operation, this concept represents the most advanced solution for sustainable steelmaking in industry.

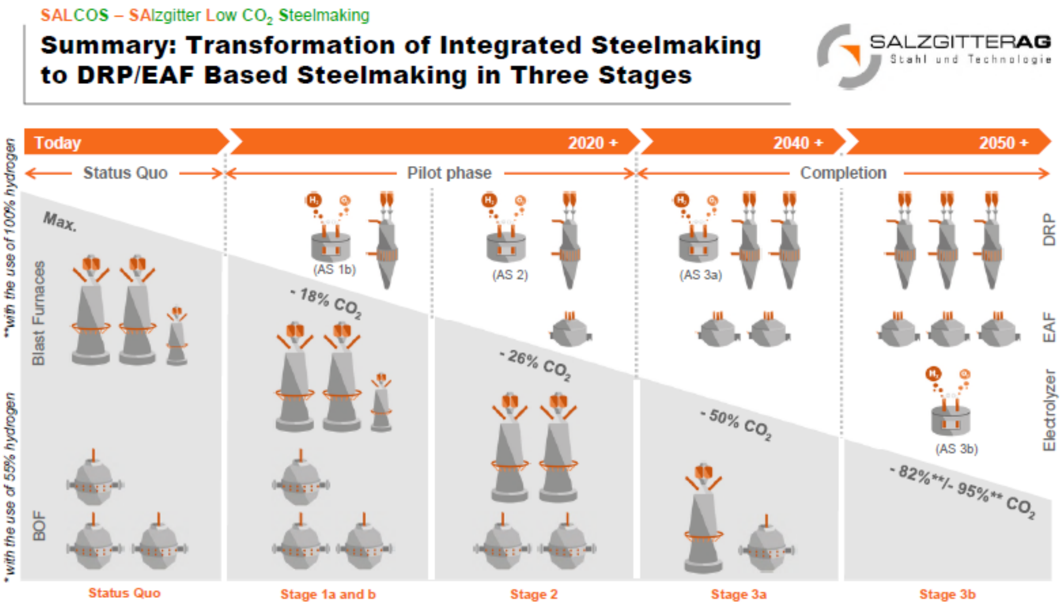

Fig. 6 – The maximum CO2 reduction possible by the SALCOS® concept in this ultimate configuration is 95% (source: SZAG).

The next step will be the incorporation of a melt shop to produce steel via electric arc furnace route. Distributing HCDRI to EAF (via hot charging / pneumatic transport system – HYTemp) as well as to BF's or storage bin in different ratios provides highest flexibility in raw materials (Hot DRI, Cold DRI, Scrap) and performance control. This allows further to shut down one of the three BF's in operation in order to reduce the CO_2 emissions significantly up to 25%. Further steps in this transformation process are principally based on the same approach as the steps before, leading to the complete change of steelmaking from the blast furnace/basic oxygen technology to the direct reduction/electric arc furnace route. With the final configuration the entire integrated steelworks will be transformed and the resulting reduction in CO_2 emissions will be in the range of 95% (Figure 6). That means vice versa the remaining carbon footprint of Salzgitter site will be only 5% compared to the present day. Figure 7 visualizes the potential transformation process with / without CO_2 off-taking and utilization the of hydrogen in varying quantities as well as its effects on carbon footprint from BF/BOF route to DRP/EAF route in general (approximate values).

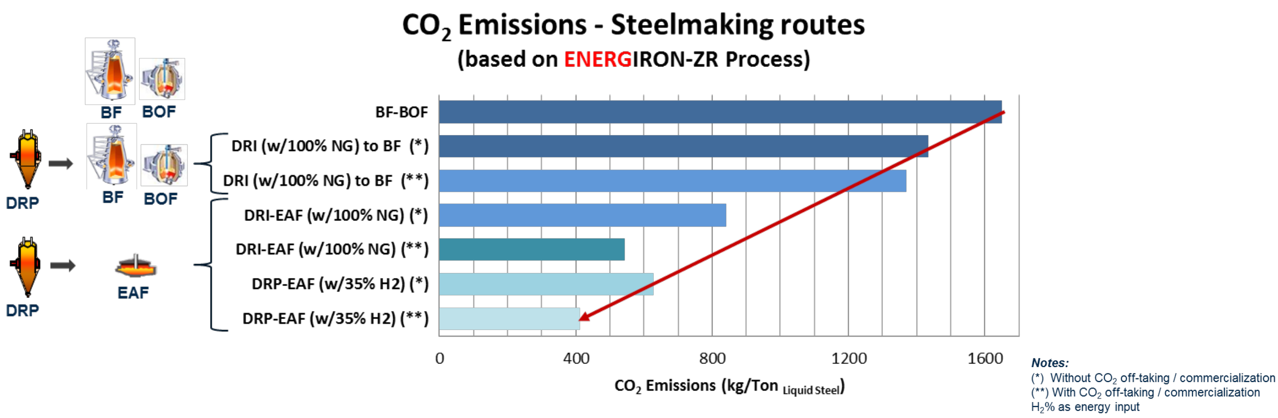

Fig. 7 – Stepwise transformation process w/wo CO2 off-taking and utilization of hydrogen in varying quantities

This stepwise transformation process requires next to considerable investments in new plant equipment adjustments to given regulatory and economic framework to avoid unreasonable OPEX increase, for instance taxes on electrical energy (EEG allocation). These conditions have firstly to be adapted in order to facilitate the realization of the transformation project. To make this transformation process and its effects on greenhouse gas emissions more tangible, the numbers has been transformed into analogies (Figure 8). With the final configuration of Salzgitter site after transformation the reduction of CO2 emissions will be equivalent to CO2 emission of around 4,6 million cars (around 10,5% emissions of all cars in Germany per year) or is equivalent to 500 million trees (around 6,6 times Berlin city area covered with trees).

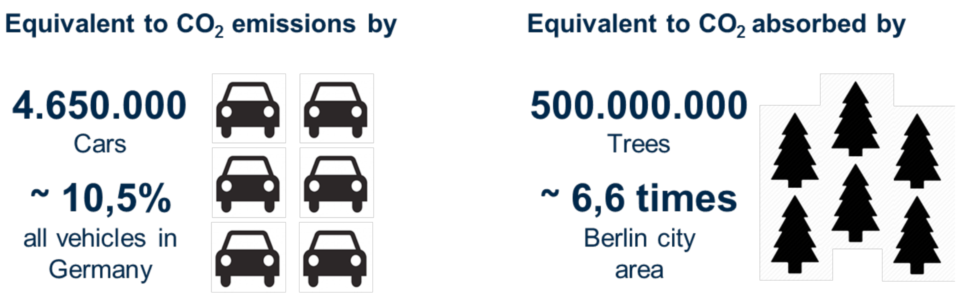

Fig. 8 – Equivalents for CO_2 reduction of SALCOS project

These comparisons visualizing the tremendous effects and the important role steel industry can play in future. The major problem remains and can be reduced to a simple formula: European steel industry has to act locally on CO_2 emissions, but to compete worldwide. This implies the willingness of society to invest (public funding) to avoid carbon leakage to non-ETS countries and to keep steelmaking in Europe beneficial and economic.

Summary / Final statements

Tenova provides sophisticated technologies and features to meet future needs of our customers. Considering present challenges for iron- and steel makers e.g. rapidly changing conditions on political and social level, approval procedures for new installations, raw material quality and availability, different energy sources on changing price levels, stricter environmental regulations and greenhouse gas emission reduction targets, the upcoming hydrogen era as well as overcapacities in the market, Tenova with its experience, know-how and technologies can support the transformation of making steel in future in a more sustainable, environmental-friendly and economic way.

Key attributes we see are:

- Highest raw material flexibility and cost control
- Ability to fulfill todays and future environmental regulations for all process conditions
- Utmost reliability and repeatable process and energy efficiency
- Ability for adjustments and modifications to meet future challenges

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