

DELIVERABLE REPORT



Green Industrial Hydrogen via steam electrolysis



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Table of acronyms

BAT	Best Available Technology
BF	Blast Furnace
BOF	Basic Oxygen Furnace
CCS	Carbon Capture & Storage
CCU	Carbon Capture & Usage
CDA	Carbon Direct Avoidance
CDRI	Cold Direct Reduced Iron
COG	Coke Oven Gas
DRI	Direct Reduced Iron
DRP	Direct Reduction Plant
EAF	Electric Arc Furnace
Fe°	Metallic iron
GHG	Green House Gas
HBI	Hot Briquetted Iron
HDRI	Hot Direct Reduced Iron
LHV	Lower Heating Value
LS	Liquid Steel
NG	Natural Gas
PG	Process Gas
PGH	Process Gas Heater
PT	Pneumatic Transport
SALCOS	Salzgitter Low CO2 Steel Production
StE	Steam Electrolyser
ZR	Zero Reformer



Preamble

Hydrogen – either as feedstock or energy carrier – holds a huge potential to decrease significantly the carbon intensity of the European industry and mobility sectors.

In order to comply, however, with the European Commission’s roadmap for moving towards a competitive low-carbon economy in 2050, the origin and production route of the hydrogen is essential to reach the overall greenhouse gas emission targets.

The key to that will be the hydrogen production from renewable energies and low-carbon or carbon neutral energy sources. Since these energy sources will be a limiting factor in the future, energy efficient technologies and production routes are most promising.

One of the promising technologies is the steam electrolysis based on Solid Oxide Electrolysis Cells (SOEC). Due to a significant energy input in form of steam from waste heat of industrial processes, the steam electrolysis not only is most energy efficient but achieves outstanding electrical efficiencies of up to 84 %_{el,LHV}.

Because of that and to increase the Technology Readiness Level (TRL) of the steam electrolysis, the central element of the GrInHy2.0¹ project is to manufacture and operate the world’s first steam electrolyser of the Megawatt class at an integrated iron-and-steel works.

During the project period of four years, the prototype will run a minimum of 13,000 operational hours. While using steam from waste heat of the steelmaking processes, the electrolyser shall produce at least 100 tons of “green hydrogen” which will be fed into the existing hydrogen infrastructure. Then, the hydrogen will be used for the steel annealing process by substituting liquified hydrogen from a steam methane reformer. In the future, however, this hydrogen could also substitute the coal and coke used for steelmaking from iron ores with the long-term objective of CO₂ reduction in the steel industry.

This deliverable assesses the use of hydrogen in Direct Reduction (DR) Plants regarding the potentials for CO₂ avoidance in iron-and-steel works.

¹ GrInHy2.0: Green Industrial Hydrogen via steam electrolysis

1 Introduction

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 worldwide predominant technology. 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 difficult to predict market conditions are topics iron- and steel makers has to deal with. These terms are representing threats, but also opportunities; those who act now will also play an important role in the future. Especially three main facts have to be considered long-term.

- First, the long-term asymptotic target world steel demand will be covered by 80 - 85% with recycled steel scrap and only 15 – 20% has to be substituted by iron ore considering worldwide economic growth and the related product lifecycle in emerging markets. Medium-term the share of scrap in steel production will be of around 50 – 60%. The current share of scrap-based steel production in the EU is around 40%.
- Second, stricter environmental regulations will force iron- and steelmakers, driven by policy and society, to change carbon intensive processes into more sustainable and environmental-friendly solutions. With reference to the fast change in terms of induction furnaces in China in 2018 forced by the Chinese government, such moves have to be even more considered in future. The iron- and steel industry is responsible for more than 7% of global anthropogenic CO₂ emissions.
- Third, the huge investments in renewable energy and hydrogen producing facilities especially in Asia sound the bell for the upcoming hydrogen era. In combination with the fact that in iron metallurgy carbon can be replaced by hydrogen in direct reduction processes the way how to make steel is already defined.

For Europe: the EU wants to cut its CO₂ emissions by 40 % the next years and the Iron and Steel industry is one of the largest producers of CO₂ emissions. 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. As international agreements (see Paris 2015) and national laws increasingly call for a reduction of dust, NO_x and CO₂ emissions, advanced post-combustion and fume treatment solutions must be implemented to meet these targets. Emerging countries as China will most probably follow this approach.

What the steel industry and especially integrated plants need is a paradigm change to be prepared for the future, to fulfil environmental regulations specifically on carbon footprint reduction and to cope with raw material availabilities as well as final product qualities. Additionally, considering future scrap compositions and qualities the steel plant of the future will be more a recycling facility dealing with various input materials than a simple melting unit. This creates additional business and will be the key to remain competitive.

In order to evaluate scenarios and solutions for the future of integrated steel mills in a holistic approach the following general objectives and topics has been defined:

- Techno-economic analysis through a dedicated cost model
- Optimization of the energy management strategy of the overall system thanks to a model predictive control loop

- Verification of business cases in the iron & steel industry considering boundary conditions from renewable electricity sourcing and hydrogen certification
- Evaluation of business cases for further industries and applications
- Investigation of the most economical system operation modes
- Elaboration of future roll-out scenarios for hydrogen technologies in combination with the European steel industry
- Ecological assessment of various End-of-Life scenarios of the StE technology focusing on closing material cycles

1.1 Hydrogen for steel industry

In today's integrated iron-and-steel works with subsequent warm and cold rolling, hydrogen is used at steel annealing processes, e.g. batch annealing. Annealing is a heat treatment for processed steel to restore its ductility. Depending on the required material properties the steel is heated to a suitable temperature in an inert atmosphere with shares of hydrogen.

Hydrogen has two functions:

- Prevention of oxidation during the process, and
- Increasing the heat transfer of the inert atmosphere due to its higher heat transfer coefficient than most other inert gases.

Since hydrogen is needed for a reducing atmosphere during annealing, the hydrogen has to fulfil high quality standards of 3.8 hydrogen (<10 ppmv O₂, < 200 ppmv N₂).

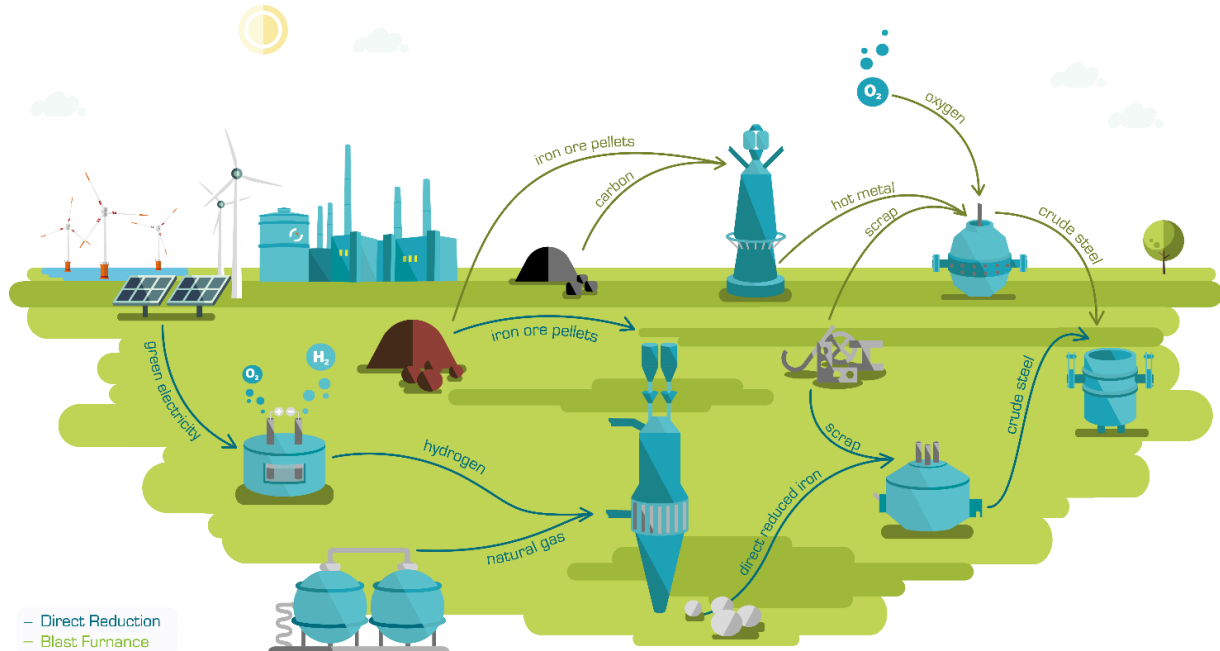


Figure 1: Comparison of today's Blast Furnace route vs. Direct Reduction route

Next to annealing processes the major advantage of hydrogen in iron- and steelmaking industry is the ability to replace carbon for reduction processes. This metallurgical legality leads to the fact that the usage of hydrogen in steel industry can substantially reduce carbon footprint. This requires a transformation of entire steelmaking process from BF/BOF route towards electric steelmaking route using mainly direct reduced iron (DRI) as input material in BF and EAF (see Figure 1) and the related usage of hydrogen in DRP. This transformation

process can be realized by a stepwise replacement of BF/BOF plants by DRP and EAF's facilities in consideration of smart material and gas distribution networks and sophisticated logistics. The inherent flexibility of Tenova's ENERGIRON-ZR process using alternative reducing gases such as hydrogen on a large scale represents a great potential to reduce coke and carbon carriers in primary steel production and so reduce carbon footprint tremendously.

Hence the ENERGIRON-ZR process has been used as reference for all calculations and findings in this report.

In order to evaluate the potential of hydrogen usage in integrated steel works as replacement of carbon carriers in reduction processes and its related effects on the overall carbon footprint the following subtasks and objectives have been defined:

- Study on hydrogen's CDA potential for integrated iron-and-steel works
- Identification of optimal system dimensions based on mass and energy balances
- Evaluation of indispensable process transformation to perform with maximum efficiency

Hydrogen use in Direct Reduction (DR) Plant:

- Modelling of different levels of H₂ usage in the DR Plant (based on the ENERGIRON ZR Process) up to 70% hydrogen use in energy requirements. Simulations and modelling include main consumption figures, expected DRI quality, expected CO₂ emissions and effluents, depending on the percentage of H₂ used in the process.
- Extrapolation of experimental data from pilot plant campaigns with up to 90% H₂, to simulate the use of H₂ in the ZR DR Plant.
- Calculation of CO₂ emissions from DR Plant and in combination with integrated BF-BOF mill, as H₂ feed is increased to 100%.

Use of DRI in the Blast Furnaces (BF):

- Analysis of the use of DRI in BF-BOF mill to reduce CO₂ emissions, based on previous DRI/HBI industrial data. Modelling of the additional benefits by using High-C DRI in the BF's to further reduce the CO₂ emissions in integrated mills, including H₂ feed and energy optimization related to gases distribution (COG, BFG, ...) and exported / imported power.
- Definition of implementation plan in steps to reduce CO₂ emissions up to 80% in integrated BF-BOF mills by using High-Carbon DRI from DR plants, use of H₂ and incorporation of EAF.
- Further H₂ use up to 100% modelling and experimentation for DR plants, in combination with BF-BOF mills.

2 CDA potential for integrated iron- and-steel-works based on hydrogen

General statement: The presented results and CO₂ mitigation effects are based on system boundaries including the processes of liquid metallurgy (sintering plant, coking plant, blast furnaces, steel works with basic oxygen furnace), the power plant and also the downstream processes including hot rolling mill.

In order to comply with environmental regulations related to reduction of CO₂ emission in steelmaking industry, the foreseen approach is shifting from the coal-based BF-BOF to the

gas-based DR-EAF route. Considering that replacing coal by natural gas through the ENERGIRON process reduces the CO₂ emissions already to 32% compared to the BF-BOF route, in case CCU is possible; the elimination of carbon footprint to about 1% is possible using H₂ generated from electrolysis powered by renewable energy for reduction of iron ores. This technological scheme, experience and economics are presented in this analysis.

In order to follow the sustainable approach, the only way to produce carbon-free H₂ is based on water electrolysis by using renewable energy to provide the required power, thus eliminating the carbon footprint (CDA) for ironmaking and steelmaking (Figure 2) finally.

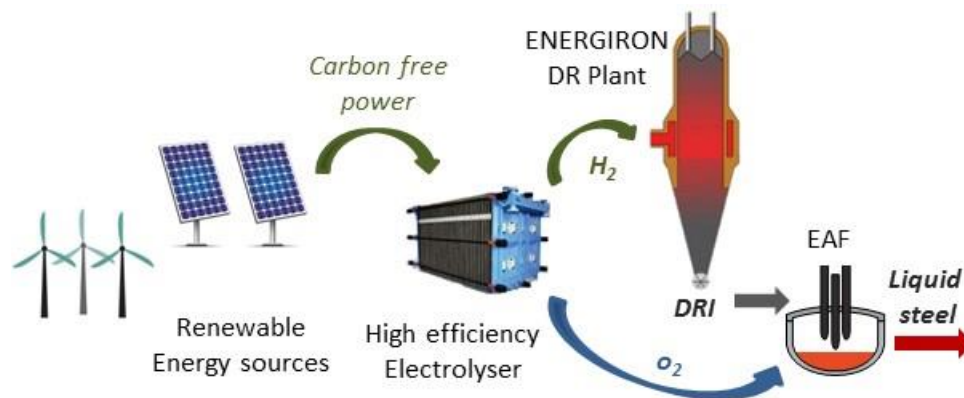


Figure 2: Carbon-free steelmaking route based on ENERGIRON ZR Process

For carbon-free H₂ generation, there are different available electrolyser technologies, such as Proton Exchange Membranes (PEM), Atmospheric Alkaline Electrolysers (AAE) with units already in operation for high purity H₂ and power consumption ranging from 3,8 to 4,6 kW/Nm³ of H₂, and High Temperature Electrolysers (HTE), currently at smaller scale, using steam with related power consumption of about 3,6 kW/Nm³ of H₂. Larger PEM and AAE modules are in the range of 4.000 Nm³/h of H₂ production rate.

2.1 The direct reduction process as base for the transformation process

The ENERGIRON ZR Process

Developed in pilot plant in the 1980's and successfully started at full industrial operation in 1998, the ENERGIRON ZR process scheme (Figure 3) is due to its inherent flexibility in reducing gases including hydrogen the base for all calculations and findings in this report.

The basic scheme configuration of the ENERGIRON process is the same regardless the source of reducing gas make-up; natural gas (CH₄), hydrogen (H₂), reformed gas from external steam/NG reformer, syngas from coal gasifiers or COG, depending on availability and operates without the need of an external reformer. As indicated in Figure 3, 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, 3) to a smelting furnace for production of pig iron and 4) direct to CDRI.

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.

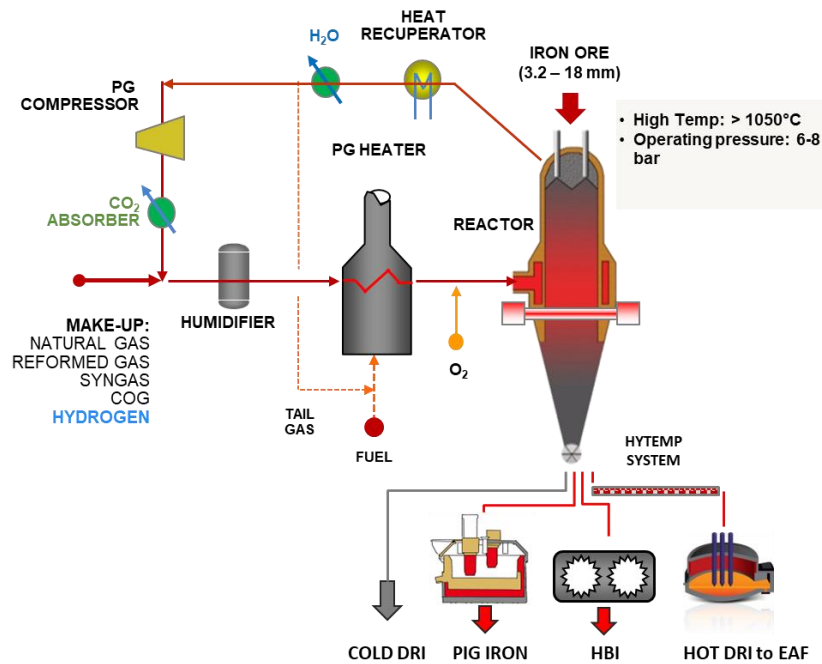
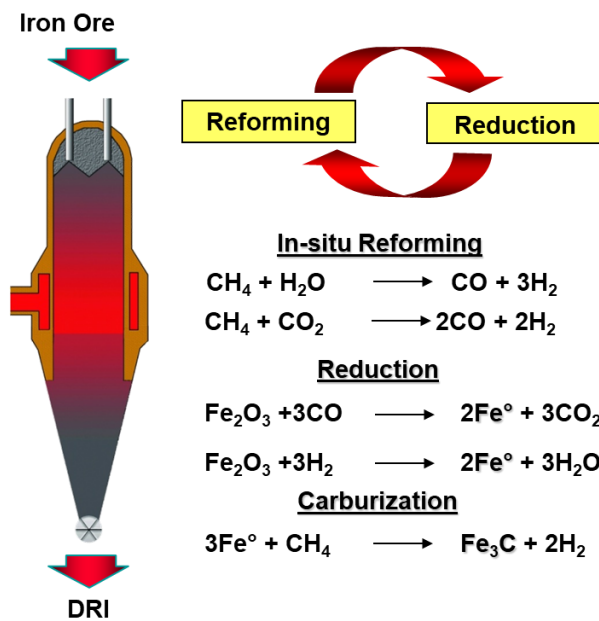


Figure 3: Process scheme of ENERGIIRON ZR Process

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.

The NG reforming, iron ore reduction and DRI carburization (see Figure 4) are taking place in the same reactor. The Catalyst is the same iron (Fe) in DRI being produced and always renewed. The high temperature in the reactor favours in-situ reforming and reduction process, the high pressure allows better flexibility for small diameter of reactor to comply with fluidization and larger height for better gas distribution. The high temperature of reducing gas (~1080°C), overcomes temperature losses of hot DRI, discharged at >700°C for hot DRI/HBI production.



In-situ Reforming:

Conditions for Hydrocarbons reforming:

- presence of Oxidants and hydrocarbons (H_2O , CO_2 , $\text{C}_n\text{H}_{2n+2}$)
- high temperature $>1050^\circ\text{C}$
- presence of catalyst (*)

Iron Oxides Reduction:

The conditions for the reduction of iron oxides are:

- presence of reductants
- $(\text{H}_2 + \text{CO}) / (\text{H}_2\text{O} + \text{CO}_2) \gg 1$
- high temperature $>1050^\circ\text{C}$
- presence of iron oxides

Figure 4: Reforming and reduction process in the same reactor – no external reformer

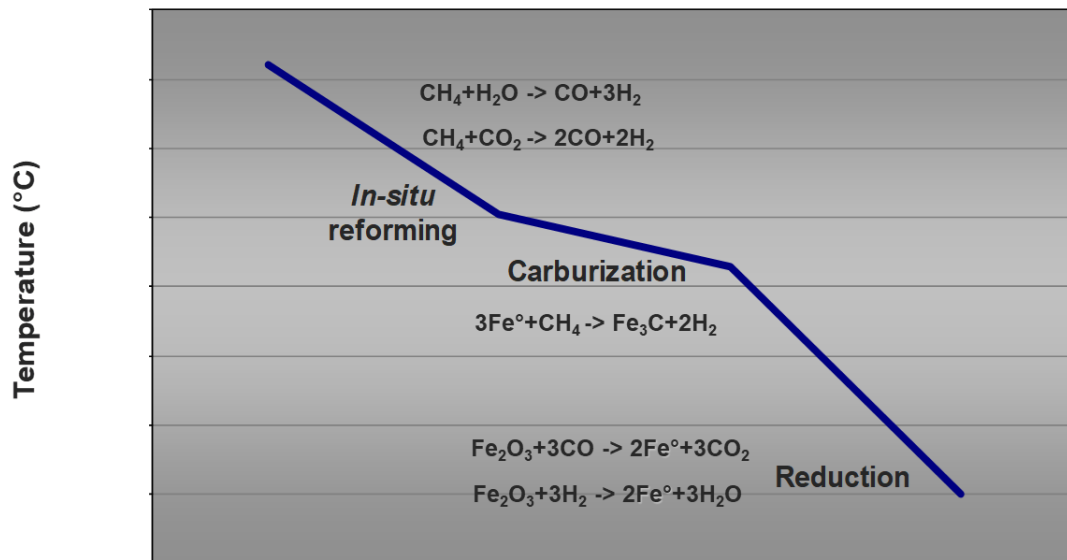


Figure 5: Reforming, reduction and carburization and thermodynamic potentials

Figure 5 visualizes the different processes in the reactor – reforming, carburization and reduction – as parameter of temperature.

The ENERGIRON-ZR process is the only direct reduction process (with TRL ≥ 7) suitable to operate with up to 100% hydrogen (or other reducing gases), thus the process represents the key technology and main part to put the CDA approach into practice.

2.2 CO₂ absorption system as important feature of the process scheme

One of the key features of this technology is the inherent selective elimination of both by-products of the reduction process: H₂O and CO₂. As indicated in Figure 6, about 62% of total carbon input to the process and fuel is selectively removed via a CO₂ amines-based system. This CO₂ at high purity can be and is being commercialized (CO₂ off-taking) as valuable by-product for different industries as Carbon Capture and Use (CCU) approach.

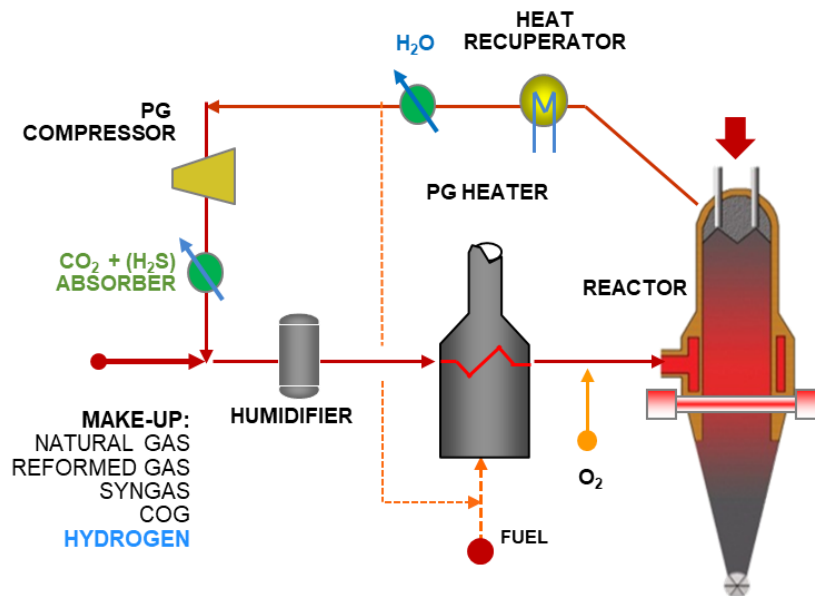


Figure 6: Selective CO₂ removal system as inherent part of process scheme

This system is based on chemical absorption and the usage of α MDEA (activated Methyl-diethanolamine). The absorbing solution also removes from the process recycling gas all H₂S along with the CO₂ in the absorption unit. The H₂S and traces of other gases are part of the untreated CO₂ gas stream, which can be further purified downstream by a desulphurization system for commercialization.

The system, normally used in petrochemical applications, comprises of an absorption unit, where the CO₂ from the recycling gas is captured by chemical and physical absorption with the amines as function of its partial pressure ($p_{\text{CO}_2} = P \cdot X_{\text{CO}_2}$). This process takes place at high pressure (DRP condition) and low temperature.

2.3 Evaluation / Definition of a stepwise process transformation

In order to derive general statements of the potential carbon footprint reduction with hydrogen Salzgitter Flachstahl GmbH (SZFG) as reference for an integrated steel works has been analysed in detail. In a first step the base case has been defined (Figure 7). The base case comprises all carbon / energy based inputs and outputs of the existing integrated plant with some roundings.

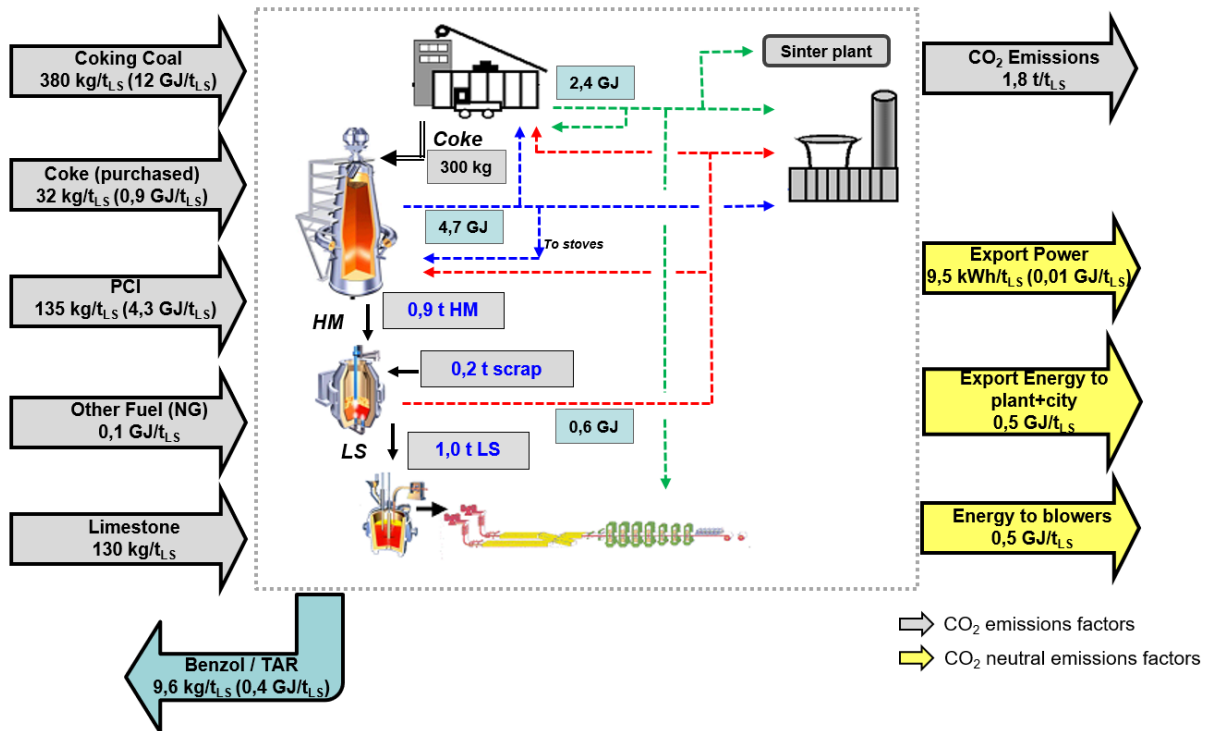


Figure 7: Balance sheet “Base Case” of the reference steel works SZFG

In further steps several modifications (implementation of direct reduction plant, melt shop) has been analyzed in terms of carbon / energy based inputs and outputs (see Figure 8).

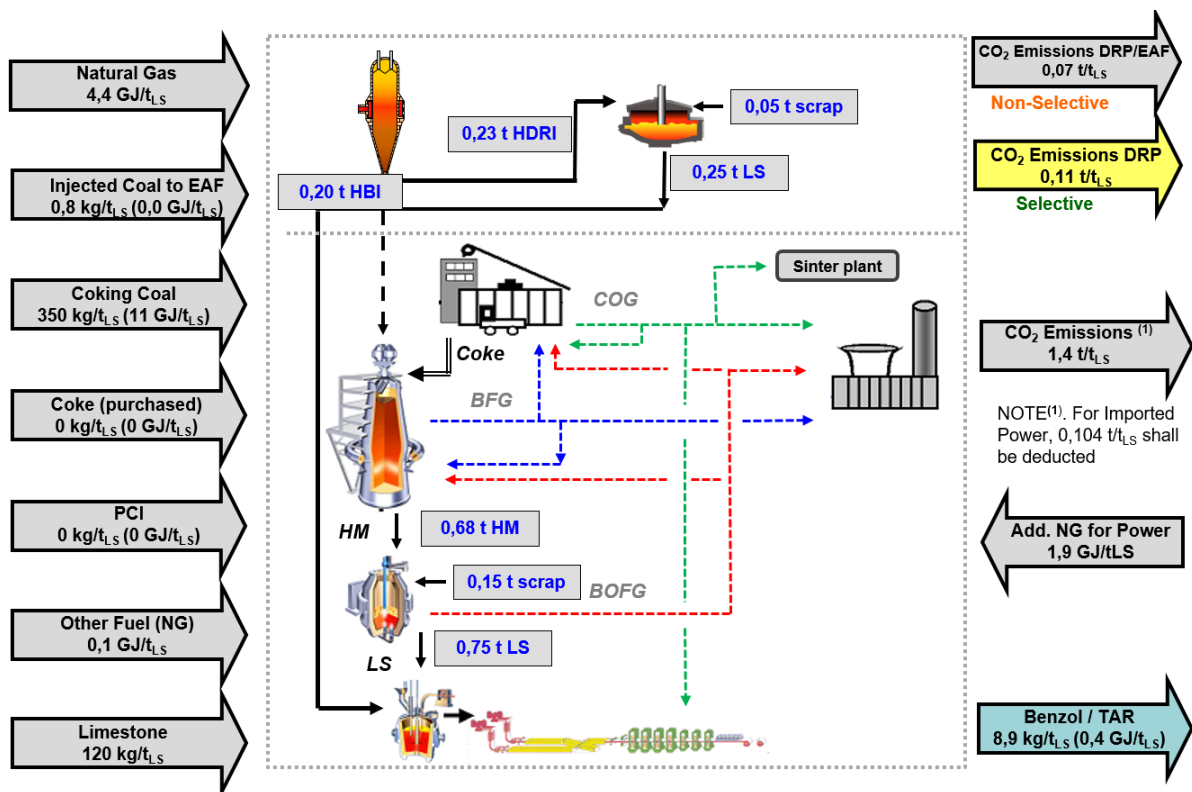


Figure 8: Balance sheet “Stage 2”: Impact of DRP (100% NG) and EAF

As result a stepwise transformation process of integrated iron and steel works towards direct reduction and electrical energy based steelmaking processes has been defined in order to show the possibility to follow stricter CO₂ reduction targets in Europe after 2030. This transformation process, realized in subsequent steps, reduces the environmental impact in terms of CO₂ emissions up to around 95% depending on framework conditions.

- The transformation steps in detail:

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 (see chapter 5).

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, see chapter 4).

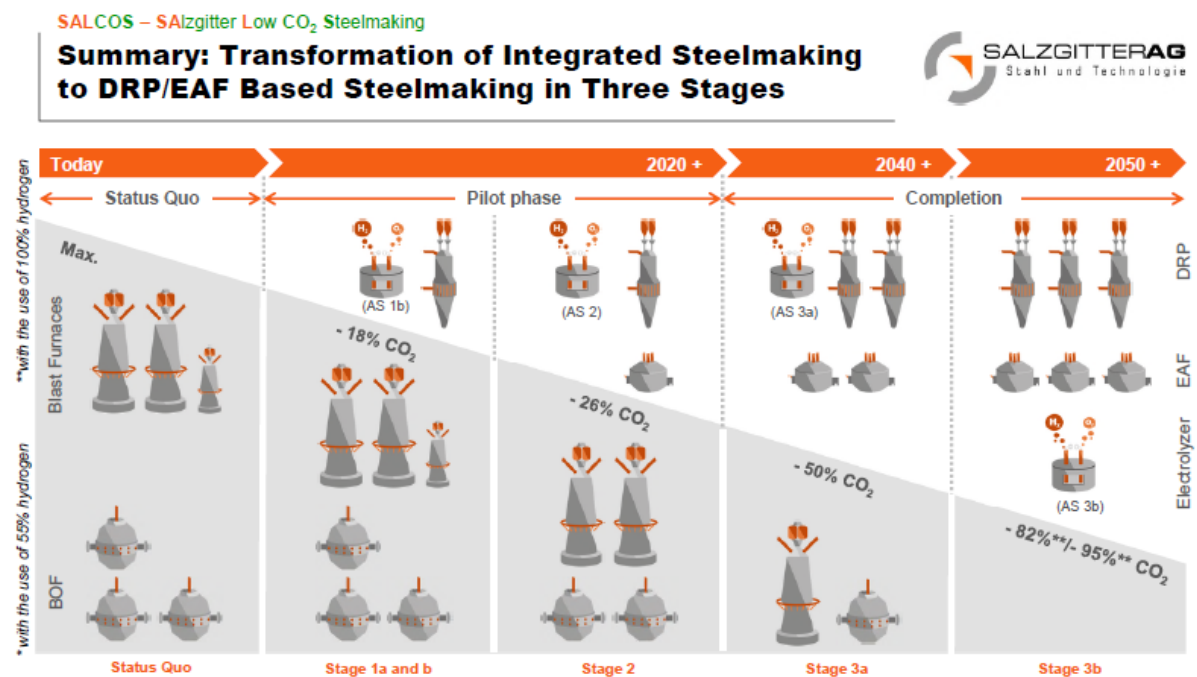


Figure 9: Stepwise transformation process of reference integrated steel works SZ

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 CO₂ 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 CO₂ emissions will be in the range of 95% (Figure 9). That means vice versa the remaining carbon footprint of Salzgitter site will be only 5% compared to the present day. And also this remaining 5% can be reduced by using biogenic carbon for the EAF electrodes and as reduction agent in the EAF. The following diagrams visualizing the potential transformation process with and without CO₂ off-taking and utilization 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, derived from results of Salzgitter case). Additionally, the impact of location and the corresponding carbon footprint of electrical energy (location factor in kg CO₂/kWh) has been considered. The diagram 1 and 2 visualizing the emission reduction potentials with a location factor of 0,5 kg CO₂/kWh.

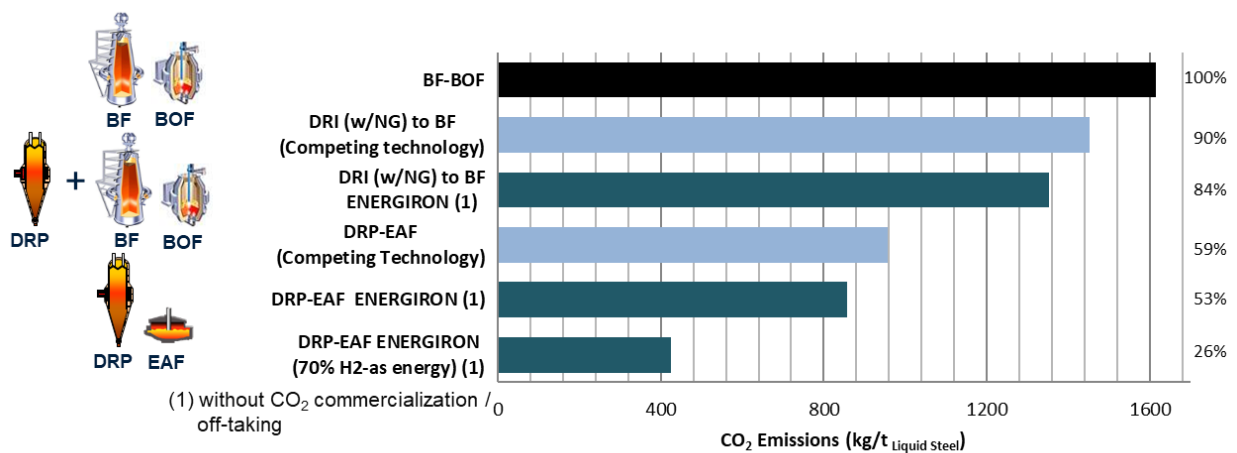


Diagram 1: CO₂ emission reduction potential without CO₂ off-taking / location factor 0,5 kg CO₂/kWh

The DRI/HBI feeding into the BF will improve the BF operation in terms of productivity increase, Hot Metal (HM) production increase of about 7-8% per each 10% of burden metallization and the environmental impact is reduced (Lower coke/PCI rate; about 6-7% per each 10% of burden metallization)

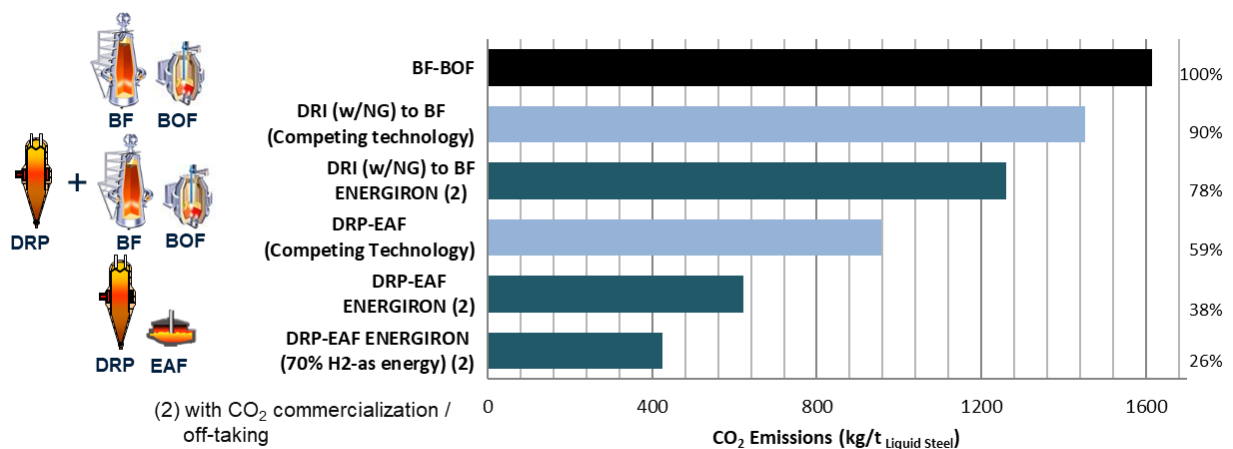


Diagram 2: CO₂ emission reduction potential with CO₂ off-taking / location factor 0,5 kg CO₂/kWh

For a location where power is impinged with $\sim 0,5 \text{ kg CO}_2/\text{kWh}$: The ENERGIRON DR-EAF route has $\sim 50\%$ less CO_2 emissions vs. integrated mill and $< 40\%$ with CO_2 off-taking. Further reduction to $< 30\%$ with H_2 use can be achieved.

The diagram 3 and 4 visualizing the emission reduction potentials with a location factor of $0,0 \text{ kg CO}_2/\text{kWh}$, means all electrical energy is supplied by renewable energy sources.

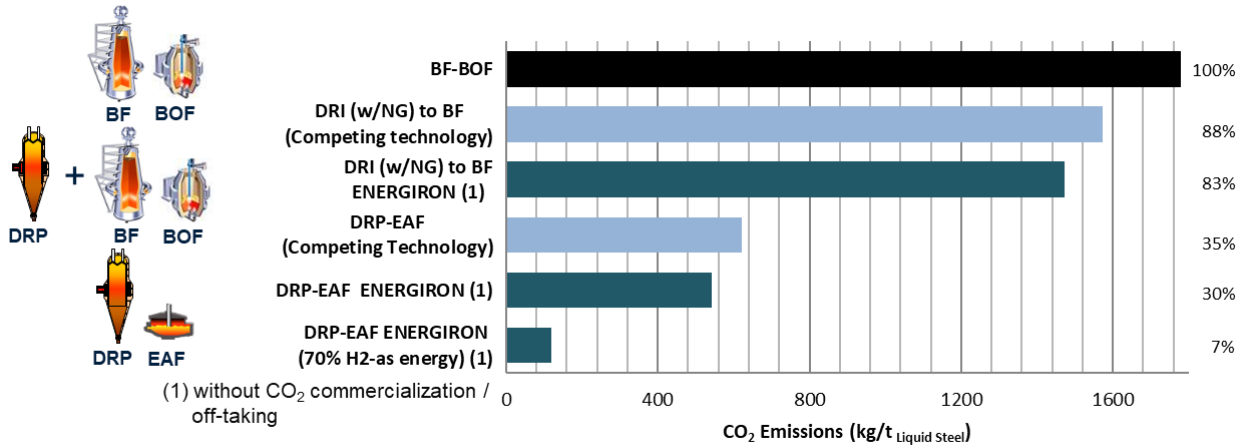


Diagram 3: CO₂ emission reduction potential without CO₂ off-taking / location factor $0,0 \text{ kg CO}_2/\text{kWh}$

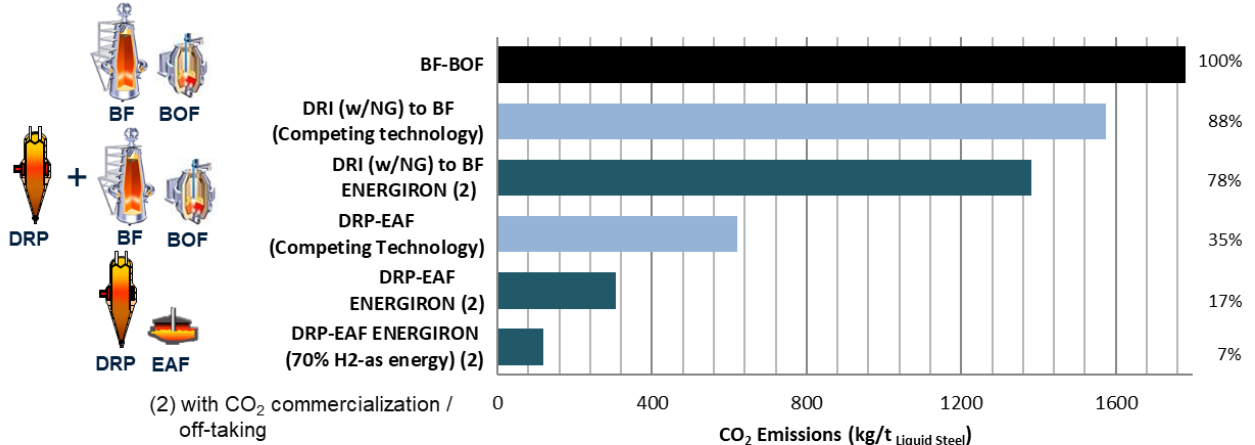


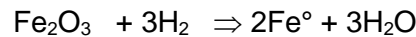
Diagram 4: CO₂ emission reduction potential with CO₂ off-taking / location factor $0,0 \text{ kg CO}_2/\text{kWh}$

For a location where power is CO₂-neutral: The ENERGIRON DR-EAF route has just $\sim 30\%$ of the CO₂ emissions compared to an integrated mill and $< 20\%$ with CO₂ off-taking. Further reduction to $< 10\%$ with $70\% \text{ H}_2$ use can be achieved.

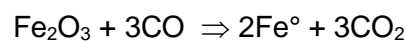
3 Hydrogen use in Direct Reduction (DR) Plants

3.1 Reduction of iron ores with H₂

The gas reducing agents are CO, H₂ and mixtures of both. Thermodynamics of reduction of iron oxides, dealing primarily with equilibrium between iron oxides, CO and H₂, provides the potential for the process to occur. This is indicated by the Gibbs Free Energy (ΔG°):



$$\Delta G^\circ @900^\circ\text{C}: -11.103,3 \text{ kJ/kg mol H}_2; \Delta H_{\text{rxn}} @900^\circ\text{C}: +21.881,0 \text{ kJ/kg mol H}_2$$



$$\Delta G^\circ @900^\circ\text{C}: -8.149,4 \text{ kJ/kg mol CO}; \Delta H_{\text{rxn}} @ 900^\circ\text{C}: -11.401,1 \text{ kJ/kg mol CO}$$

As observed, thermodynamically H₂ reduces iron oxide more easily than CO, as per change of Gibbs free energy. On the other hand, the exothermic or endothermic behavior is indicated by the enthalpy change (ΔH_{rxn}) of the corresponding reactions.

Iron ore reduction with only H₂ is a highly endothermal reaction, favored at high temperatures and requiring high H₂ concentrations at lower temperatures. While reduction with CO is an exothermal reaction, favored at low temperatures taking place at lower CO concentrations. 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.

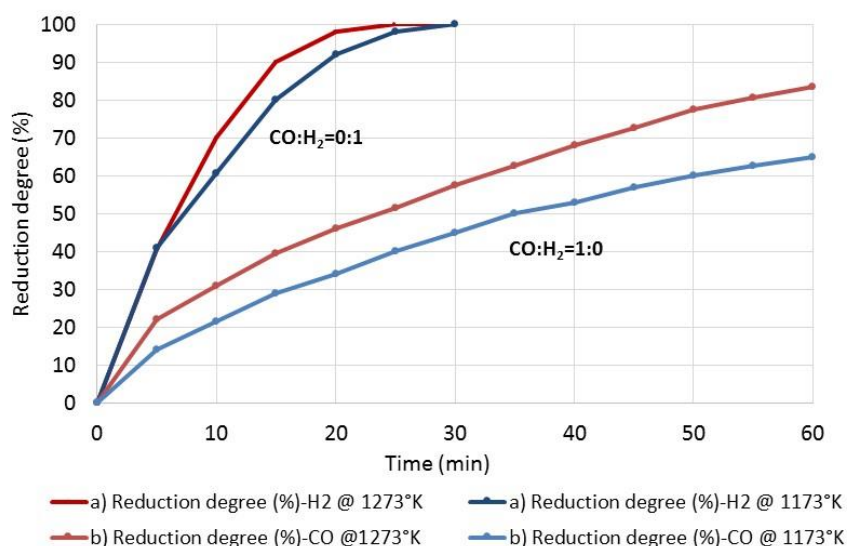


Figure 10: Change of reduction degrees with time for CO:H₂: 0:1; CO:H₂: 1:0

Kinetically, the effect of temperature on the extent of iron ore reduction has been investigated using gases with different H₂/CO ratios. The changes of reduction degree at two levels of temperature (900°C and 1000°C) for CO/H₂ ratios of 1:0 and 0:1, are indicated in Figure 10.

In general, the higher the temperature the faster the extent of the reduction process, whether the reducing agent is H₂ or CO. Hence, the reduction of iron ore with H₂ is more than 4 times faster as compared to CO; i.e. 98% reduction in ~20 min vs. 83% reduction in 60 min at 1000°C.

Reasons are:

- The equilibrium of H₂ decreases with increasing temperature because it is an endothermic reaction, leading to a higher reducing potential at high temperature, and as a result, the driving force of the reduction reaction is enhanced;
- The high temperature contributes to a high mass transfer coefficient.

On the other hand, iron ore reduction with CO requires lower reducing gas temperature because of the exothermic reaction behaviour, and kinetically is much slower than the reduction with H₂.

3.2 The ZR process scheme for intensive H₂ use

For the case of H₂, the same concept applies. The only difference is that for H₂ utilization higher than ~73% (energy) or ~90% vol. at reactor inlet, the process scheme is simplified by eliminating the need of selective CO₂ removal system. For higher H₂ concentrations, any carbon input to the system, via NG, along with other components like N₂, are eliminated through the tail gas purge from the system, which is used as fuel in the gas heater (Figure 11).

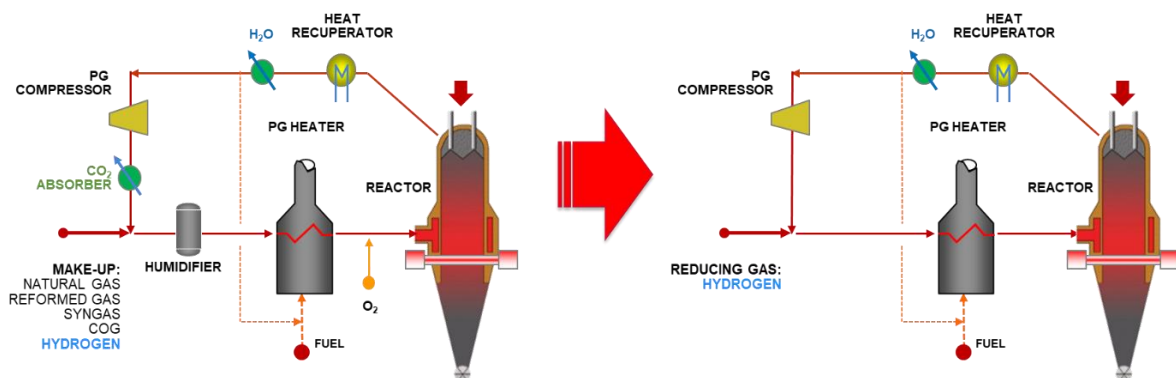


Figure 11: Simplification of process scheme with the usage of > 90% H₂ vol.

In terms of energy consumption, the impact of H₂ (figures as % of total energy input), as compared to NG is indicated in Figure 12. As observed, there is saving in energy consumption of ~2,0 GJ/t in the DR plant.

In any case, the use of H₂ is more effective in terms of energy requirements since this reductant is already available and there is no need of NG reforming for generation of reducing gases (see Figure 12). On the other hand, there is no credit of %C in DRI.

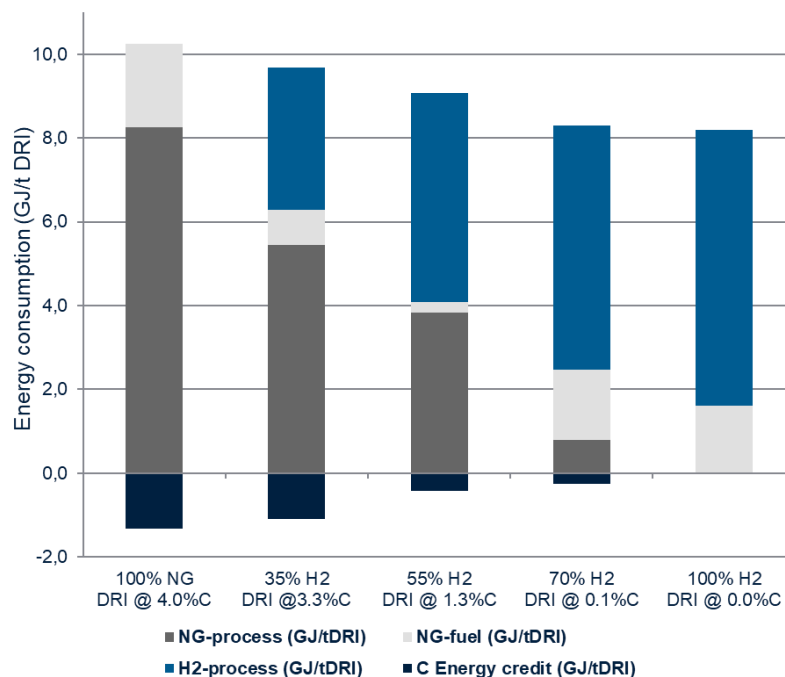


Figure 12: Energy consumption figures for NG (3,5% C) and H₂ (0% C) as % energy input

3.3 EAF operation and effects on overall CO₂ balance

EAF's operations to melt DRI are based on certain DRI characteristics for reducing remaining FeO and promoting foaming slag. The optimum %C in DRI is based on the amount of DRI in the mix feedstock for certain steel quality, specific cost scenario, among others, but the trend is the use of High-Carbon DRI due to the additional chemical energy input to the furnace. H₂-based DRI will imply to feed low or 0% C DRI, which will require particular EAF melting practices. In fact: Minimum carbon content in DRI or carbon injected separately is required for EAF steel production operations.

Options are:

- 1) To produce DRI from high Fe content premium iron ores, with the optimized/highest metallization (~96%), thus minimizing the FeO content. Considering the stoichiometric requirements for reduction of remaining FeO and minimum melting needs, the %C in DRI will be ~0,8 – 1,2%. This will imply certain NG injection to the DR plant, which is possible for the ENERGIRON process operating with ~90% (vol.) H₂, as already demonstrated in our pilot plant.
- 2) To produce DRI from selective iron ores chemistry with 100% H₂ and 0% C, which will be fed to an EAF, requiring a minimum carbon injection of 12-15 kg C/t_{LS}, particular melting operations and slag engineering practices.

Both options are workable but in terms of overall CO₂ emissions related to the integrated system DRP-EAF, while option 1) will result in emissions of about 150 kg CO₂/t_{LS}, option 2) will represent just about 50 kg CO₂/t_{LS}. In terms of overall decarburization Option 2) would be the preferred choice for H₂-based steelmaking. In general, for production of H₂-based DRI, the possibilities are: HDRI for direct charging to EAF or HBI for storage and transport to prevent re-oxidation due to the nil %C content.

4 Use of DRI (HBI) in the Blast Furnaces (BF)

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 13 are based on the use of traditional DRI/HBI which implies carbon levels not higher than 2.0% C.

Definition of Burden Metallization:

$$\% \text{Burden Mtz} = \text{Fe}^\circ \text{ in HBI} / \text{Fe}_{\text{tot}} \text{ (pellets+lump ore+HBI+sinter)}$$

Example: DRI @ 94% Mtz and iron ore with 67,9% Fe tot → 85,1% Fe metallization in the HBI and approx. 35% Burden Mtz for 400 kg_{HBI}/t_{HM}.

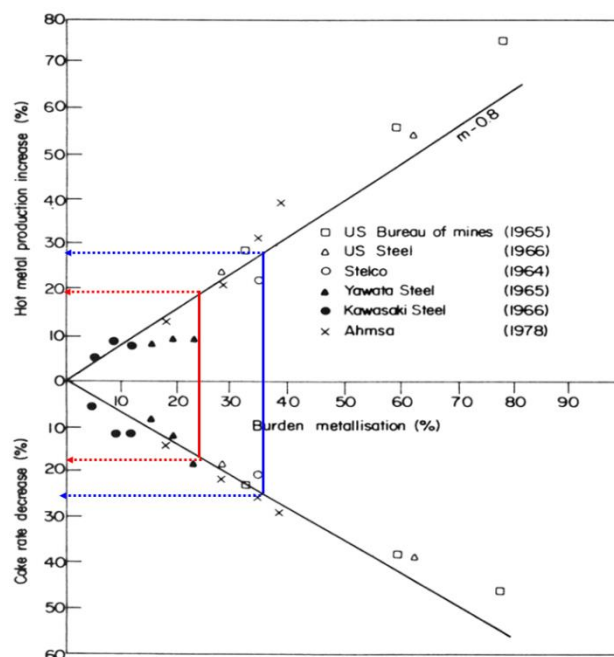


Figure 13: Correlation between Coke Rate vs. Hot Metal vs. Burden Metallization

A further decrease of the PCI/coke consumption and increase of the BF productivity can be reached whenever High-C DRI/HBI ($\geq 4.0\% \text{ C}$) is used instead of standard DRI/HBI ($< 2.0\% \text{ C}$). In the ENERGIIRON DRI, more than 90% of the carbon contained in the High-C DRI is in the form of iron carbide (Fe_3C). 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.
- 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 CO₂-neutral, and depending on DR Plant location (abroad or on-site), the use of High-C DRI/HBI reduces the CO₂ Emissions in 26,3% or 17,6% respectively, depending on DRP location.

For the use in blast furnaces (BF) the DRI is compacted (briquetted) into HBI in order to avoid re-oxidation effects and losses via dust emissions. The following cases were analysed to show the effects on productivity, HBI quality and consumption figures in relation to the hydrogen use:

- 100% Natural Gas
- 91% Natural gas / 9% Hydrogen
- 70% Natural Gas / 30% Hydrogen
- 65% Natural Gas / 35% Hydrogen
- 45% Natural Gas / 55% Hydrogen
- 100% Hydrogen

All above percentages refer to make-up reducing gases to process. For all cases, the energy requirements for fuel is only natural gas.

Cases ⁽¹⁾	In Energy (to process)	100% NG	91% NG 9% H ₂	70% NG 30% H ₂	65% NG 35% H ₂	45% NG 55% H ₂	100% H ₂	
Cases ⁽²⁾	In volume (to process)	100% NG	70% NG ⁽³⁾ 30% H ₂	38% NG 62% H ₂	30% NG 70% H ₂	19% NG 81% H ₂	100% H ₂	
Product		HBI	HBI	HBI	HBI	HBI	HBI	
Plant productivity		100%	100%	100%	100%	105%	118%	
Metallization		94%	94%	94%	94%	94%	94%	
Carbon		3,6%	3,6%	3,5%	3,3%	1,3%	0%	
Main plant inputs	Unit							
Iron ore (dry-screened)	t / t _{HBI}	1,37	1,37	1,37	1,37	1,40	1,42	
Energy source:								
- Natural Gas (process)	GJ / t _{HBI}	8,35	7,49	6,37	5,06	4,08	-	
- Natural Gas (fuel)	GJ / t _{HBI}	2,18	1,94	0,66	1,35	0,12	1,75	
- Hydrogen (process)	GJ / t _{HBI}	-	0,93	3,03	3,47	5,06	6,68	
Total Energy	GJ / t _{HBI}	10,53	10,36	10,06	9,88	9,26	8,43	
Energy source (in volume):								
- Natural Gas (process)	Nm ³ / t _{HBI}	226	203	173	137	111	-	
- Natural Gas (fuel)	Nm ³ / t _{HBI}	59	53	18	37	3	47	
- Hydrogen (process)	Nm ³ / t _{HBI}	-	86	281	322	470	620	

Table 1: Correlation of plant productivity, metallization and carbon for different reducing gas compositions (approximate figures)

Variations in higher % of hydrogen use as makeup gas in the process will result in different effects in plant operation, as follows:

- Increase of production rate.
- Carbon content in the HBI product.
- Reduction of consumption figures mainly for reducing gas, oxygen and power.
- Reduction in CO₂ emissions from the HBI plant.

The expected CO₂ emissions figures of the HBI plant, for the various operation modes, depending on the NG / H₂ proportion, are as indicated in the following graph (Figure 14):

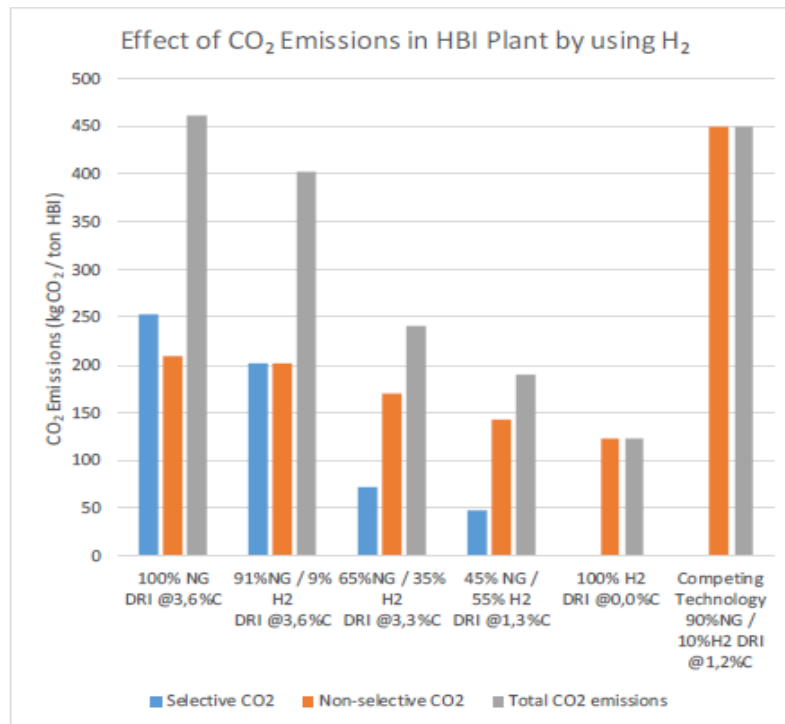


Figure 14: CO₂ emission reduction effects for different reducing gas compositions (approximate figures)

The CO₂ selectively removed in the CO₂ absorption unit can be commercialized, given additional revenues to the plant operation and further reduction of carbon footprint. The following plot shows the CO₂ emissions reduction in function of the % of H₂ use and the difference in carbon footprint in case of CO₂ off-taking.

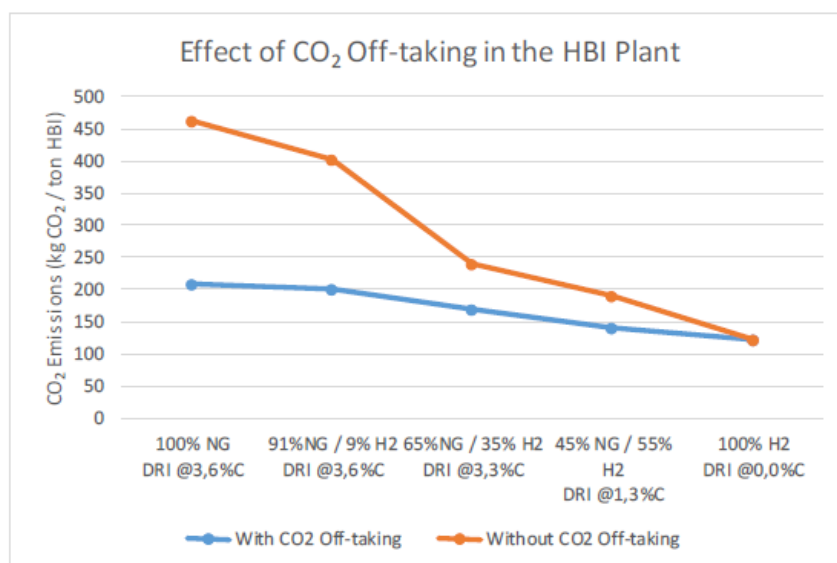


Figure 15: Effects of CO₂ off-taking in HBI plants (approximate figures)

5 Conclusion

In order to evaluate the potential of hydrogen usage in integrated steel works as replacement of carbon carriers in reduction processes and its related effects on the overall carbon footprint, the following aspects has been carried out:

- Description of the ENERGIRON-ZR process scheme as potential BAT for hydrogen usage in iron making processes (replacement of carbon carriers with hydrogen)
- Investigation / definition of a stepwise transformation process of an integrated iron and steel works towards direct reduction and electrical energy based steelmaking processes and calculation of related CO₂ emission reduction potentials based on SZFG
- Derivation of general statements for a stepwise transformation process of an integrated iron and steel works and calculation of related CO₂ emission reduction potentials
- Modelling of different levels of H₂ usage in the DR Plant (based on the ENERGIRON ZR Process) up to 70% hydrogen use in energy requirements.
- Extrapolation of experimental data from pilot plant campaigns with up to 90% H₂, to simulate the use of H₂ in the ZR DR Plant.
- Investigation and evaluation of the usage of DRI / HBI in Blast Furnaces (BF) and correlated effects on CO₂ emission reduction
- Definition of implementation plan in steps to reduce CO₂ emissions in up to 80% in integrated BF-BOF mills by using High-Carbon DRI from DR plants, use of H₂ and incorporation of EAF.
- Further H₂ use up to 100% modelling and experimentation for DR plants, in combination with BF-BOF mills.

The technology for production of DRI based on up to 100% H₂ is already available by using the ENERGIRON ZR process. Either HDRI for direct charging to EAF or HBI for storage/abroad transport are the recommended products to prevent re-oxidation of the DRI with 0% C. "Green" H₂ from high efficiency electrolyzers powered by electricity from renewable sources is the right approach for carbon-free steelmaking.

It can be stated that with shifting from the coal-based BF-BOF to the gas-based DR-EAF route in conjunction with the usage of hydrogen as reducing gas the CO₂ emissions / carbon footprint of the entire iron-and-steel works can be reduced by more than 90%.

6 Outlook

In a next step (see Subtask 5.2.1, Upscaling effects and CAPEX/OPEX estimations for European steel works, TENOVA, M25 - M48) the economic effects for hydrogen based iron-and steelmaking has to be analysed.

In terms of OPEX, producing hydrogen by water electrolysis implies a direct cost of the connection to the power grid. Considering ~4,5 kWh/Nm³ H₂, the energy consumption for DRI, based on the ENERGIRON ZR technology, will be ~3,0 MWh/t DRI. Since green H₂ will be produced from renewable energy, the analysis shall be made on such power cost. The point is that due to the high-power consumption for H₂ generation, the energy costs are of a high level as well. Currently, as example, in Germany the power from renewable sources has dropped to below €0,05/kWh, which would mean an equivalent of about \$16/GJ for DRI



production, which is still high. However; costs related to water make-up, CAPEX of electrolyser modules, H₂ storage and transport (when applicable) and CO₂ emissions targets, with corresponding credits, shall be taken also into account in the cost equation.

According to IRENA (International Renewable Energy Agency), electricity from renewables will soon be consistently cheaper than from fossil fuels. By 2020, all the power generation technologies that are now in commercial use will fall within the fossil fuel-fired cost range, with most at the lower end or even undercutting fossil fuels. Record low auction prices for solar photovoltaic (PV) energy in 2016 and 2017 in Dubai, Mexico, Peru, Chile, Abu Dhabi and Saudi Arabia have shown that an LCOE (Levelised Cost of Electricity) of \$0,03/ kWh is possible from 2018 and beyond, with the right conditions. By 2019, the best onshore wind and solar PV projects will be delivering electricity for an LCOE equivalent of \$0,03/kWh, or less, with CSP (Concentrated Solar Power) and offshore wind capable of providing electricity very competitively. Increasingly in the future, many renewable power generation projects can undercut fossil fuel-fired electricity generation without financial support.

To be on a competitive scenario in terms of green hydrogen-based DRI production, as per current electrolyser efficiency and without CO₂ credits, the electricity from renewable sources should be ≤ \$0,03 /kWh. CAPEX for electrolyser has to be also significantly reduced.

Hence, upscaling calculations and investment estimations for reference steel plants (CAPEX, OPEX), ROI calculations to show CO₂ mitigation potential using results from previous WPs has to be carried out.