Hydrogen-based steelmaking

Environmental and climate change pressures are demanding that the steel industry decarbonises. Tenova, with its ENERGIRON experience, is well based to help achieve the goal of carbon-free steelmaking. The use of hydrogen as an iron ore reductant is proven at laboratory and pilot plant level with ENERGIRON technology, utilising over 90% H₂ as the reductant. Demonstration plant trials are being progressed, however, to be competitive with fossil fuel-based ironmaking, H₂-based DRI production, the electricity from renewable sources needs to be reduced to $0.03/kWh or less, and CAPEX has to be significantly reduced.

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As environmental and climate change concerns increase, the steel industry is seriously evaluating how its carbon footprint can be reduced. Overall, Europe is a leader in this field, researching the intensive use of hydrogen-based iron reduction as a long-term substitute for carbon-based processes. A major step, as described in the European Steel Technology Platform (ESTEP) Strategic Research Agenda, is the initiative on ultra-low carbon future European steelmaking. Specific future aspects of ESTEP will cover issues related to H₂ supply, use, transport and energy storage in general. Some projects oriented on this target are:

- ThyssenKrupp with the Carbon2Chem® project aimed at using CO₂ emissions from steelworks and surplus energy from renewable sources for chemical production. Currently shifting to the carbon direct avoidance (CDA) approach.
- Voestalpine, Siemens and Verbund with the H₂FUTURE project; building a pilot facility for green H₂ at Linz.
- SSAB, LKAB and Vattenfall with the HYBRIT initiative based on carbon-free steelmaking by using H₂. Thanks to the unique characteristics of its ENERGIRON process and its specific expertise in direct reduction of iron with H₂, Tenova HYL was a perfect fit and was contracted for the HYBRIT project. The pilot plant will be located in Luleå, Sweden, and is expected to begin operations in 2020.

Salzgitter SALCOS (Salzgitter Low CO₂ Steelmaking) project with high-C DRI as feed to BF and EAF (replacing BOF) in combination with the GrinHy project to generate H₂ via reversible, high temperature electrolysers through renewable energy, to be used for DRI production. The SALCOS project, a study initiated by Salzgitter AG together with Tenova/Danieli and Fraunhofer-Gesellschaft (FhG) in 2015, is designed to analyse the capabilities of already existing technologies to reduce greenhouse gas emissions, to investigate implications on integrated steel works and to demonstrate the possibility of generating a significant contribution to carbon footprint reduction.

ENERGIRON PROCESS

The ENERGIRON process (the HYL DRI technology jointly developed by Tenova and Danieli) began in the 1950s with the installation of the first industrial scale gas-based direct reduction plant at Hylsa in Monterrey, Mexico, using H₂-rich gas (in a ratio of H₂/CO~5) as the reducing agent. Subsequent developments have included selective CO₂ removal for increasing process efficiency while reducing energy consumption and providing a practical solution for CO₂ capture and commercialisation (CCU), developing the ZR (reformerless) variant for further process efficiency while producing high carbon DRI (>3%C), using the breakthrough reliable Hytemp system for hot DRI transport, and EAF feeding by environmentally friendly, pneumatic transport.

The ENERGIRON ZR process to produce DRI (see Figure 1, left) is a major step forward in reducing the size and improving the efficiency of direct reduction plants. Reducing gases are generated by in-situ reforming within the reduction reactor, feeding natural gas as make-up to the reducing gas circuit and injecting oxygen at the inlet of the reactor. The basic ZR process permits the direct use of natural gas but the plants can also use conventional steam-natural gas reformers as an external source of reducing gases. Other
reducing agents, such as hydrogen, syngas produced from coal gasification, pet coke and similar fossil fuels, and coke oven gas, are also potential sources of reducing gas, depending on the particular situation and availability. In any variant, the same basic process is used regardless of the reducing gas source. The current configuration of this technology employs a continuous shaft furnace-based process, with both the product quality and process efficiency having been significantly optimised over the years. ZR technology is currently the most flexible option for producing DRI based on its uniquely simple process configuration and its wide flexibility for using different energy sources and available raw materials, hence it was readily adaptable for use with hydrogen. A modern ZR unit is shown in Figure 2.

HISTORICAL USE OF H₂ IN DR-EAF STEELMAKING
Historically, the steelmaking route based on DR-EAF has always been characterised by the use of H₂, which is normally generated from natural gas (NG) through catalytic reformers. Since the hydrocarbon source is NG, the H₂ produced can be of variable concentration, and mixed with CO, depending on the oxidant ratio being used.

Since the 1950s, there are now hundreds of DR and hydrogen plants in operation using HYL/ENERGIRON technology with reformed gas as the source of reducing gas and a conventional NG/steam reformer. Specifically, there are more than 40 HYL/ENERGIRON plants having used this type of NG reformer in the steel industry. The typical operation characteristics for these plants and for the competing technology (Midrex) are shown in Table 1. Higher H₂ levels are indicated for ENERGIRON.

In any process variant, as long as NG is used as the primary source of H₂ generation, there will be CO₂ as by-product, which is emitted in both, the DR plant and the melt shop.

EXPERIENCE USING OF H₂ IN ENERGIRON REDUCTION OF IRON ORE
Thermodynamically H₂ reduces iron oxide more easily than CO (Gibbs free energy). Iron ore reduction with H₂ is a highly endothermic reaction, favoured at high temperatures, and requiring high H₂ concentrations at lower temperatures. Comparably, reduction with CO is an exothermic reaction, favoured at low temperatures and taking place at lower CO concentrations[2]. However, thermodynamic data do not provide information on the rate at which the reduction reactions would take place. This depends on the reaction kinetics, and the process parameters can be only determined by experimental testing.

Kinetically, the effect of temperature on the extent of iron ore reduction has been investigated using gases with...
different H₂/CO ratios [3]. The degree of reduction at 1,000°C for CO/H₂ ratios of 1:0 and 0:1, are indicated in Figure 3. In general, the higher the temperature the faster the reduction process, whether the reducing agent is H₂ or CO. However, the reduction of iron ore with H₂ is more than four times faster as compared to CO.

ENERGIRON ZR FOR INTENSIVE H₂ USE

The basic configuration of the ZR process is the same regardless of the source of reducing gas make-up. The only difference is that for H₂ utilisation higher than ~73% (energy) or ~90% volume at the reactor inlet, the process scheme is simplified by eliminating the need for a 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 1 shows the process schematic at high H₂ concentration. [1].

In terms of energy consumption, the impact of H₂ (as % of total energy input), as compared to NG is indicated in Figure 4. There is a saving in energy consumption of ~2.0 GJ/t in the DR plant, since H₂ is already available, and there is no need of NG reforming; however, there is no credit of %C in the DRI [4].

DEMONSTRATION/ PILOT PLANT EXPERIENCE WITH ~100% H₂

In addition to the vast industrial experience using H₂ in reformed gas, in the 1990s Tenova HYL carried out extensive tests at a pilot plant (see Figure 5) with ≥90% (vol.) H₂; producing H₂ from reformed gas from an industrial DR plant by the water-gas shifting reaction and CO₂ removal [1].

The demonstration/pilot plant at HYLsa Monterrey had a production rate of 36tDRI/day with full flexibility to produce CDRI, HDRI for HBI production, and HDRI for direct pneumatic transport to an adjacent pilot plant EAF. This plant also included full capability for synthesis of all types of reducing gases; from 100% H₂ to 100% CO, including reformed gas, typical coke oven gas and gases from coal gasification. In fact, the ZR process was developed and demonstrated in this facility in the 1980s.

The experimental campaign included 15 different process conditions, depending on the DRI type and quality to be achieved. This included production of CDRI and HBI with metallisation of 94-96% and carbon from 0.2 ~1%, depending on the CO-CH₄ concentration in the circuit.

These tests provided all necessary information to define:
- Process and design parameters mainly related to reducing gas optimised flow-temperature correlation
- DRI quality in terms of metallisation and carbon content
- Optimisation of operating pressure, reactor L/D ratio, solids residence time (τ), consistently achieve the DRI...
quality, determination of fluidisation factor \( f \) to ensure proper gas velocities and distribution through the solids bed, among others.

These campaigns with high \( \text{H}_2 \) confirm the fact that ENERGIRON technology is already available for the use of 100\% \( \text{H}_2 \). All the required data for design and operation under this condition is available and can be directly applicable to any existing and/or new DR plant installation.

**PRODUCTION OF ‘GREEN’ \( \text{H}_2 \)**

Currently the only way to produce carbon-free or ‘green’ \( \text{H}_2 \) is from water electrolysis using renewable energy to provide the required power, thus eliminating the carbon footprint (CDA) for ironmaking and steelmaking. An example based on Tenova’s ENERGIRON direct reduction process is shown in Figure 6.

There are a number of electrolyser technologies currently available to produce hydrogen from water. Proton exchange membranes (PEM) and atmospheric alkaline electrolysers (AAE) are already in operation for high purity \( \text{H}_2 \), with power consumptions ranging from 3.8 to 4.6 kW/Nm\(^3\) of \( \text{H}_2 \). These produce about 4,000Nm\(^3\)/h of \( \text{H}_2 \), which is sufficient for operation of a DR module of about 40,000-50,000t/yr DRI depending on the availability of alternate fuels. Replication of available modules will be proportionally required for larger DR plant sizes [1]. High temperature electrolysers (HTE), using steam and with power consumptions of 3.6kW/Nm\(^3\) of \( \text{H}_2 \) are also currently used at smaller scale.

**CHALLENGE OF MELTING \( \text{H}_2 \)-BASED DRI IN EAF**

EAF operations to melt DRI are based its chemical and physical characteristics, the need to reduce the remaining FeO, and to promote foaming slag formation. The optimum %C in DRI is based on the amount of DRI in the mix feedstock for a given steel quality and specific cost scenario at each plant, however, the trend is towards the use of high carbon DRI due to the additional chemical energy input to the furnace. \( \text{H}_2 \)-based DRI is lower in C so will require specific EAF melting practices, including, for instance, more carbon injected separately via lances [1].

There are two basic options for DRI production:

1) Produce DRI from high Fe content premium iron ores, with the optimised/highest metallisation \((\sim 96\%)\), thus minimising the FeO content. Considering the stoichiometric requirements for reduction of the remaining FeO and minimum melting needs, the %C in DRI will need to be \(0.8-1.2\%). This will involve the ENERGIRON process operating with \(90\%\) (vol.) \( \text{H}_2 \) plus some NG injection.

2) Produce DRI with 0%C from selective iron ores via 100\% \( \text{H}_2 \) reduction in the DR plant and which will be fed to an EAF requiring a minimum carbon injection of 12-15kg C/tLS, specific melting operations and slag engineering practices.

Both options are workable but in terms of overall CO\(_2\) emissions related to the integrated system DR-EAF, option 1) will result in emissions of about 150kg CO\(_2\)/tLS, and option 2) will produce about 50kg CO\(_2\)/tLS. Thus in terms of overall decarbonisation, option 2) would be the preferred choice for \( \text{H}_2 \)-based steelmaking.

**ECONOMICS OF \( \text{H}_2 \)-BASED IRONMAKING**

In terms of OPEX, producing hydrogen by water electrolysis implies a direct cost of the connection to the power grid. At a value of \(\sim 4.5\text{kWh}/\text{Nm}^3 \text{H}_2\), the energy consumption for DRI, based on the ENERGIRON ZR technology will be \(\sim 3.0\text{MWh}/\text{t DRI}\). Since the \( \text{H}_2 \) will be produced from renewable energy, any cost analysis should be made on such a power cost. Currently this is high compared to fossil fuel power generation. However, costs are falling. In Germany, for instance, the power cost from renewable sources has dropped to about \$0.05/kWh, which would mean an equivalent of about \$16/GJ for DRI production, which is still high when compared to typical DRI energy-related production costs. Costs related to water make-up, CAPEX of electrolyser modules, \( \text{H}_2 \) storage and transport (when applicable) and CO\(_2\) emissions targets, with corresponding credits, also need to be taken also into account in the cost equation [1].

According to IRENA, the International Renewable Energy Agency [5], electricity from renewables will soon be consistently cheaper than from fossil fuels. They estimate that 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 energy (PV) 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 will undercut fossil fuel-fired electricity generation, without financial support.

To be competitive in terms of green H2-based DRI production, as per current electrolyser efficiency and without CO2 credits, the electricity from renewable sources should be ≤$0.03/kWh. CAPEX has to be also significantly reduced. This may be possible within the coming years.

CONCLUSIONS

- Environmental and climate change pressures will demand that the steel industry decarbonises
- The use of hydrogen as an iron ore reductant is proven at laboratory and pilot plant level
- Tenova’s ZR technology, utilising over 90% H2 as the reductant, has been proven at pilot plant stage and is part of the HYBRIT fossil fuel-free steelmaking project
- To be competitive with fossil fuel-based ironmaking, H2-based DRI production (using current electrolyser efficiency and without CO2 credits), the electricity from renewable sources needs to be reduced to $0.03/kWh or less, and CAPEX has to be significantly reduced.
- Tenova, with its ENERGIRON experience, is well placed to help achieve the goal of carbon-free steelmaking.

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REFERENCES