Optimizing hydrogen-based steelmaking

The use of hydrogen for steelmaking is a means of reducing the industry's carbon emissions. Tenova senior consultant Pablo Duarte outlines the technology company's optimized steelmaking scheme based on hydrogen produced by renewable energy as the primary source

A current trend in the steelmaking industry is towards decarbonization to comply with environmental regulations and to take a 'green' approach to steel production. There are two clearly identified efforts - carbon dioxide (CO_2) capture and commercialization (CCU) and the use of hydrogen (H_2) for carbon direct avoidance (CDA).

Europe is leading the trend towards the intensive use of hydrogen for steelmaking. 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. Other initiatives are now being taken in China through The National Development and Reform Committee, oriented not only to the circular economy and comprehensive utilization of resources, but also to the innovative use of carbon-free reduction processes of iron oxides for steelmaking.

A fundamental ingredient for fossil-free steelmaking is the hydrogen-based reduction of iron ores, for which carbon-free or 'green' hydrogen is produced from water electrolysis powered by renewable energy.

The use of hydrogen, already used for direct reduction (DR), can be significantly optimized in the overall scheme for steelmaking, including electric arc furnaces (EAF) and related heat-recovery technologies. Tenova has designed technology for the overall integration for an optimized steelmaking scheme based on hydrogen produced by renewable energy as the primary source.

Hydrogen in ENERGIRON DR

Steelmaking based on the DR-EAF route has always used hydrogen, which is normally generated from natural gas (NG) through catalytic reformers. Since the hydrocarbon source is NG, hydrogen is produced in different concentrations, mixed with carbon monoxide (CO), depending on the oxidants ratio being used ($CH_4 + H_2O = 3H_2 + CO$; $CH_4 + CO_2 = 2H_2 + 2CO$).

Since the 1950s, Tenova HYL technology, later developed into ENERGIRON technology (DRI technology jointly developed by Tenova and Danieli) using reformed gas as source of reducing gas, has included a very widely used conventional steam/NG reformer. For example, there are more than 40 ENERGIRON plants that have used this type of reformer.

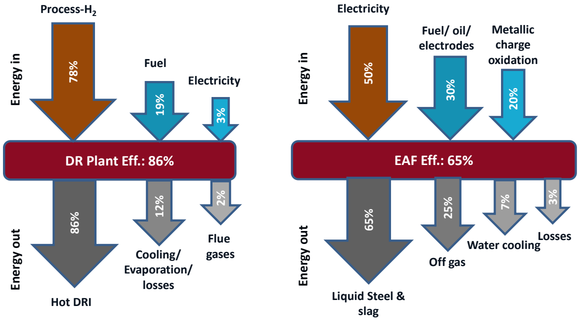
In the 1990s, Tenova HYL (Mexican company's subsidiary, specialized in DRI plant) carried out extensive tests at a pilot plant with more than 90% by volume of hydrogen produced from reformed gas from the industrial DR plant by water-gas shifting and carbon dioxide removal. That plant at Hylsa Monterrey, in Mexico, had a production rate of 36 tonnes of DRI per day with full flexibility to produce cold DRI (CDRI), hot DRI (HDRI) for hot briquetted iron (HBI) production and for direct pneumatic transport to an adjacent pilot plant EAF. It had full capability to synthesize all types of reducing gases - from 100% hydrogen to 100% carbon monoxide.

These tests provided all the information needed to define process and design parameters, mainly related to optimized gas flow-temperature correlation, and DRI quality in terms of metallization and carbon content. Additional factors were: optimization of operating pressure, reactor L/D ratio, solids residence time, to consistently achieve the DRI quality needed, and determination of fluidization factor to ensure proper gas velocities and distribution through the solids bed. The plant enabled determination of a proper design of the process and equipment for hydrogen utilization.

These tests with high hydrogen levels demonstrated that ENERGIRON technology is already available for using 100% H_2. All the data needed for design and operation with 100% hydrogen can be applied directly to existing or new DR plant installations. Features of ENERGIRON technology for the intensive use of hydrogen are: a scheme that is inherently suitable for any reducing gas make-up, specifically hydrogen; the hydrogen make-up directly replacing natural gas in the process in any proportion; wide experience of operating with high hydrogen concentration of 70% or more in existing ENERGIRON plants; a high operating pressure to safely handle hydrogen.

Green hydrogen production

Several different electrolyser technologies are available for carbon-free hydrogen generation. Atmospheric alkaline electrolysers are a mature technology in the megawatt range for industrial use, but they need to be adapted to new market requirements. Proton exchange membranes are available at a smaller, generally sub-megawatt scale. High-temperature electrolysers are still at a demonstration scale, but considerable progress has been made with them.



ENERGIRON DR Process: Overall Efficiency

EAF: Overall Efficiency

Energy Efficiency of ENERGIRON DR Plant and EAF

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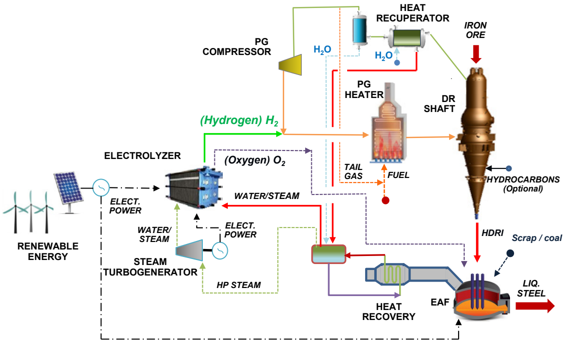

Optimized integrated scheme for H_2-based steelmaking

The atmospheric alkaline electrolyser provides a cost-effective solution for large-scale hydrogen production based on decades of knowledge and an established supply chain. At present, the largest module capacity is of 4,000 Nm^3/h H_2 with a total energy consumption of about 4.6 kWh/Nm^3 H_2 (about 74% efficiency). High-temperature electrolysers have the highest efficiency (about 84%).

DR-EAF steelmaking

A simplified process configuration when using hydrogen as the source of reducing gases makes the DR process very efficient in terms of energy consumption and scheme simplicity for the production of HDRI. The expected energy consumption for the ENERGIRON DR process with hydrogen is as low as 6.6 GJ per tonne of DRI as H_2 for the process plus an additional 1.6 GJ per tonne of DRI as fuel, and about 25 kWh per tonne of DRI for the core plant. This very low electricity consumption is not only because of the hydrogen use, but also due to the high operating pressure of the ENERGIRON system. By using hydrogen as the only source of reducing gas, there is no need for a carbon dioxide removal system, simplifying the scheme and reducing energy consumption.

In the EAF meltshop, to overcome the negative effect of the gangue in DRI, by feeding high-metallized hot DRI to the EAF, power consumption is significantly reduced to figures very close to those for 100% scrap melting. The typical power consumption for a charge of 80% hot DRI and 20% scrap is about 400 kWh per tonne of liquid steel. Feeding high percentages of a virgin metallic material such as DRI is required for the production of high-quality steels.

Optimizing the DR-EAF route

The basic configuration of a DR plant integrated with an EAF can be further optimized for the specific use of hydrogen.

For the DR plant the energy scheme is already optimized. The only sensible energy available, which may be subject to recovery, is the top gas of the reduction shaft at a temperature in the range of 400°C or less. For the hydrogen-based scheme, this sensible energy is already used in the ENERGIRON DR process for preheating the reducing gas stream upstream of the process gas heater. For the ENERGIRON DR process, the overall thermal efficiency, for production of hot DRI with 94% metallization at 700°C and using hydrogen as process gas, is as high as 86%.

There are several main DR plant components that enhance energy and water usage efficiency - not only for the DR plant, but also for an integrated scheme.

The thermal efficiency of the process gas heater is already 90%; hence there is no possible recovery from flue gases.

If the sensible energy from the top gas heat is used for external application, this energy shall be replaced by additional fuel to the process gas heater to recover the differential temperature of the reducing gas preheating. Using this sensible energy for saturated steam to be used in electrolysers will be more beneficial in the overall integrated energy scheme by reducing the power consumption for the more costly hydrogen generation (about 0.34 GJ per tonne of DRI) at the expense of some additional fuel to the process gas heater.

With regard to water recovery, an ENERGIRON DR plant typically includes a water circuit of process water for top gas cleaning, which is purged to some extent, and independently equipment-cooling water, which is used for condensing water from the top gas, generated from the reduction process, which can be recovered, treated and recycling back to electrolysers. This implies using a closed circuit for equipment-cooling water (i.e. air cooling etc.) instead of evaporative cooling towers. The economic feasibility of this approach depends on the restrictive availability of water and overall capital expenditure.

The situation for the EAF melt-shop is different. Its overall efficiency is about 65%. From the total energy input roughly 30% is lost in off-gas and water cooling. There are big efforts to optimize energy input, but these are limited by physical and process constraints. There are also efforts to exploit lost energy for steam production used as it is or for electrical energy production. Losses in off-gas and water cooling are energy streams susceptible to significant savings.

Tenova offers a technological solution to increase the efficiency of the EAF in its *i*Recovery® system, consisting mainly of recovering sensible heat from the off-gases to produce steam at 5-55 bar at 150-270°C. That steam can be used for: steel process purposes, such as vacuum for steel degassing or compressed-air generation; heating purposes, such as district heating in winter or a chiller for air-conditioning in the summer; power generation; direct use of steam, or indirectly hot water, with the required temperature and chemical characteristics to be fed to electrolysers. The additional scheme consists of the use of pressurized circulating water in the off-gases duct with constant temperature at boiling point (220°C).

The potential heat recovery through the *i*Recovery® system is about 35% of the waste gases' energy. This yields to energy recovery of 23% of the primary energy to the EAF. This recovery energy can be used either directly to the electrolyser, or as condensate-plus-electric-power feeding the electrolyser through a steam turbine, for hydrogen generation.

Optimized H_2 scheme

An optimized scheme for hydrogen-based steel production can be based on the production of DRI using 100% H_2 as process gas, the production of steel using 80% DRI and 20% scrap, the energy consumption and energy recovery figures already indicated, and controlled carbon content of DRI by introducing carburizing agents such as natural gas, carbon monoxide gas or other hydrocarbons.

Tenova's proposed concept is shown in the diagram. Although there is the possibility of using the *i*Recovery® system for steam/power cogeneration, this implies additional energy conversion inefficiencies while providing electricity to electrolysers. The suggested approach is based on the production of steam and/or hot water from sensible heat from the top gas in the DR plant and sensible heat from the off-gases in the EAF.

Steam/hot-water would be fed to the electrolysers at the required temperature and adequate chemical analysis, depending on the technology selected. This approach is simplest and attractive in terms of capital and operational expenditure.

Based on the available energy from the DR plant and the EAF, there are savings of about 9% of the total energy requirements for generating hydrogen for steel production, which is relevant, considering the current power demand of electrolyzers.