



HYL NEWS

In this issue

- Technological achievements, experience and trends in H₂-based steelmaking
- Tenova Contracted by Hybrit Development
- Ternium's 4M DR Plant 20th Anniversary

MESSAGE FROM THE CEO'S DESK

The month of December is always the right moment to look back at the year that is about to end and to see at the coming future.

The Energiron plants have had great performances in 2018, with remarkable reliability. Among the most important achievements we have to highlight the successful conversion of the first PT Krakatau Steel module from HYLIII scheme to Zero Reformer. One key ingredient of this success has been the team work between the Tenova and the PTKS teams.

The Zero Reformer process then confirms to be the state-of-the-art DRI technology, in terms of efficiency, easiness of reliable operation and product quality. And in this year indeed we celebrated the 20th anniversary of the Ternium 4M plant, the first ZR module. The superior performance of this plant has been key for Ternium to achieve the outstanding results that benefit our entire Techint Group.

And quite ahead of time, the 4M module had been the first plant in steelmaking and ironmaking that has seen the importance of CO₂ recovery and use.

The focus of the Energiron team has remained in the years on a sustainable development of our technology, that without any doubt remains the one in the market that better fits with the new revolution of Hydrogen use in the industry. We are proud that Tenova has been selected by the Swedish consortium Hybrit for their CO₂-free development.

As done in the past and in this last year, safety, reliability, innovation and sustainability will remain the pillars for the future plants and new developments.

I wish all the readers of the HYL News a great New Year!

Stefano Maggiolino

President & CEO
TENOVA HYL



VIEWPOINT

This issue of HYL NEWS deals with a very innovative technology – the use of hydrogen as a reducing gas in DR processes. Yet another innovative concept in the iron and steel industry, indeed in industries in general, is the topic of digitalization. There are a number of opportunities for the iron and steel industry in what has been called Industry 4.0, including energy and resources and the environment. In this regard, driving the development of a hydrogen-based direct reduction and steelmaking system is a major step forward.

As specifically relates to DR technology digitalization presents tremendous areas of opportunity in process control, predictive maintenance and product quality control. The subject of digitalization will be in the forefront in the coming years and is expected to revolutionize the industry. Of course, attention has to be placed on refocusing education to develop a capable workforce for the expected shift to highly skilled industrial jobs. Tenova continues to work toward developing new technologies and we expect to play a role in developing digitalization for the ironmaking industry and improved technologies for better products for our customers.

We hope you find the articles in this issue to be informative and we welcome your comments and observations. You can always find additional information through our websites at www.tenova.com and www.energiron.com

CONTENTS

- 2** Message from the CEO's Desk
- 3** Viewpoint
- 4** Technological achievements, experience and trends on H2-based steelmaking
- 11** Tenova Contracted by Hybrit Development
- 12** Ternium's 4M DR Plant 20th Anniversary
- 14** Calendar of Events

TECHNOLOGICAL ACHIEVEMENTS, EXPERIENCE AND TRENDS IN H₂-BASED STEELMAKING

INTRODUCTION

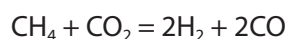
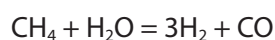
The world, and especially European iron and steel producers, need a paradigm change to be prepared for the future, to comply with environmental regulations, specifically on carbon footprint reduction, and to cope with raw material availabilities and final product qualities. There is a trend in the steelmaking industry, as part of the decarbonization of Europe's economy and the perceived future for other countries worldwide, towards hydrogen (H₂)-based iron reduction as a long-term substitute for carbon-based processes.

The ENERGIRON technology has been characterized by the inspiration of innovation. Specifically, the ZR scheme with its wide flexibility for using any energy source for direct reduction of iron ores, while keeping the same basic and proven process scheme configuration, offers the most adequate scheme for the direct use of H₂. The following is a review of the benefits and advantages of current achievements and technological experience on H₂ use for Carbon Direct Avoidance (CDA), as compared to other proposals.

H₂ has a long history of use for DR-EAF steelmaking

Historically, the steelmaking route based on Direct Reduction – Electric Arc Furnace (DR-EAF) has always been characterized by the use of H₂, which is normally generated from natural gas (NG) through catalytic reformers.

Since the hydrocarbon source is NG, H₂ is produced in different concentrations, mixed with CO, depending on the oxidants ratio being used, i.e:



Since the 1950s, the HYL/ENERGIRON technology using reformed gas as the source of reducing gas, includes a conventional steam/NG reformer of the type having hundreds of references in DR and hydrogen plants. There are more than 40 HYL/ENERGIRON plants having used this type of NG reformers. The typical operation characteristics for the HYL/ENERGIRON plants and for the competing DR technology (Midrex) are shown in Table 1.

Table 1. Characteristics of reformed gas in DR technologies

PARAMETER RELATED TO H ₂	ENERGIRON	OTHER DR TECHNOLOGY
H ₂ O/C ratio in NG 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 any case, as long as NG is used as the primary source of H₂ generation, there will be CO₂ as a by-product, which is emitted in both the DR plant and the meltshop.

How “green” H₂ should be produced

It becomes evident that the only way to produce carbon-free H₂ is from water electrolysis and using renewable energy to fulfill the required power, thus eliminating the carbon footprint (CDA) for ironmaking and steelmaking (Figure 1).

For carbon-free H₂ generation there are different available electrolyser technologies such as Proton Exchange Membranes (PEM) and Atmospheric Alkaline Electrolysers (AAE)

with units already in operation for high purity H₂ and power consumption ranging from 4.8 to 3.8 kW/Nm³ of H₂, and High Temperature Electrolysers (HTE), currently at smaller scale, using steam and with power consumption of 3.6 kW/Nm³ of H₂. Currently, larger PEM and AAE modules are in the range of 4,000 Nm³/h of H₂, sufficient for operation of a DR module of about 40,000 t/a DRI. Replication of available modules will be proportionally required for larger DR plant sizes.

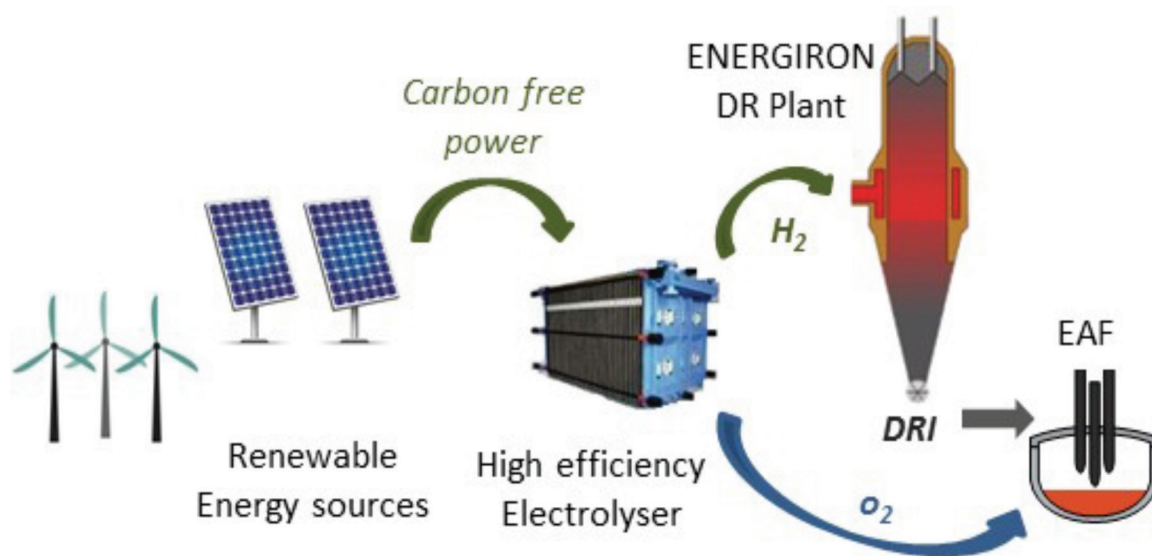


Figure 1. Carbon-free steelmaking route based on ENERGIRON ZR Process

Long lasting experience with the use of H₂ in ENERGIRON DR technology. The ZR scheme for intensive H₂ use.

The basic configuration of the ENERGIRON process is the same regardless of the source of reducing gas make-up. 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 for a selective CO₂ removal system. For higher H₂ concentrations, any carbon input to the system via NG, along with other components like H₂, are eliminated through the tail gas purge from the system, which is used as fuel in the gas heater (Figure 2).

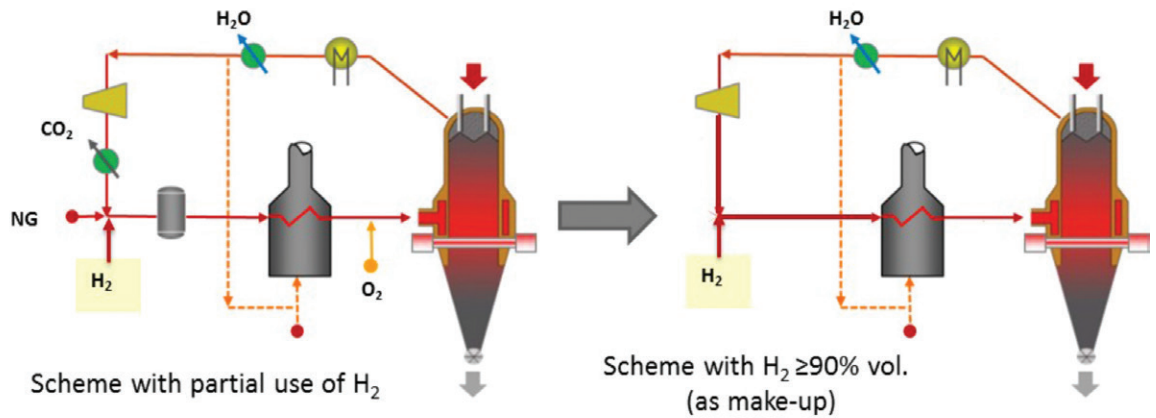


Figure 2. ENERGIION ZR Scheme with H₂ use

As observed, the ZR scheme provides a significant flexibility as compared to other DR technologies. For the HYL/ENERGIION DR technology, there are some characteristics which make this process scheme the most suitable for H₂ use:

- The ZR process scheme is inherently suitable for any reducing gas make-up, specifically H₂.
- H₂ make-up directly replaces NG in the process.
- Vast experience with high H₂ concentration (~70% vol.) in HYL/ENERGIION plants.

Since the 1950s a number of HYL/ENERGIION plants have used reformed gas as the source of reducing gas from a conventional steam/NG reformer.

In terms of energy consumption, the impact of H₂ (figures as % of total energy input), as compared to NG is indicated in Figure 3. As observed, 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 for NG reforming; however, there is no credit of %C in DRI.

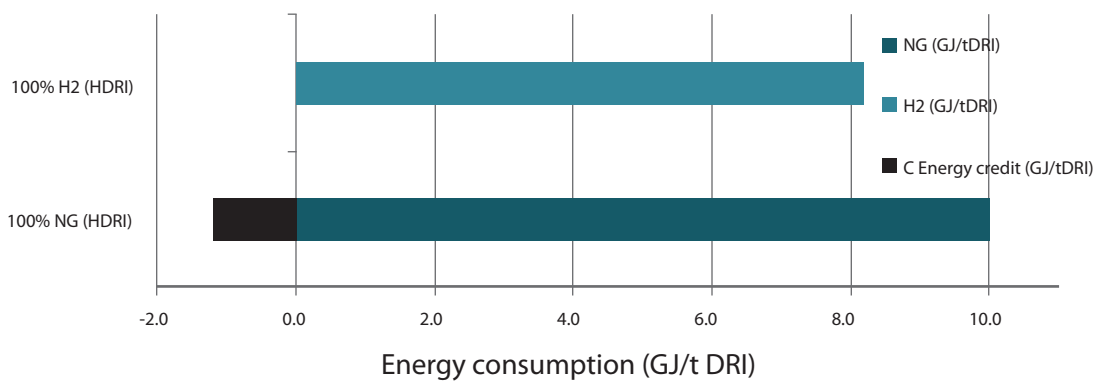


Figure 3. Energy consumption figures for NG (3,5%C) and H₂ (0%C) -% energy input

Demonstration/Pilot plant experience with ~100% H₂ use

Demonstration/Pilot plant experience with ~100% H₂ use

In addition to the vast industrial experience using H₂ in reformed gas, in the 1990s Tenova HYL carried out extensive pilot plant tests (Figure 4) with ≥ 90% (vol.) H₂; producing H₂ from reformed gas from the industrial DR plant by water-gas shifting and CO₂ removal.

The demonstration/pilot plant at Hylsa Monterrey had a production rate of 1-tonne DRI/h with full flexibility to produce CDRI, HDRI for HBI production and HDRI for direct pneumatic transport to an adjacent pilot EAF plant. This plant also included full capability for synthesis of all type of reducing gases, from 100% H₂ to 100% CO, including reformed gas, typical COG and gases from coal gasification. In fact, the ZR scheme was developed and demonstrated in this facility during the 1980s.

The experimental campaign included 15 different process conditions, depending on the DRI type and quality to be achieved.

- For CDRI conditions, a minimum required amount of NG was injected to the conical/cooling zone of the reactor. Metallization was 94%-96% and %C was ~1.0%. H₂ was controlled in ~90% vol.
- For the HDRI, HBI was produced to prevent fast re-oxidation due to low %C. Metallization was 94%-96% and %C was obtained between 0.2% – 0.8%, the latter being for the condition of some NG injection to the reduction circuit. H₂ was also controlled in ~90% vol.

These tests provided all necessary information to define:

- Process and design parameters, mainly

related to reducing gas optimized flow-temperature correlation.

- DRI quality in terms of metallization and carbon content.
- Optimization of operating pressure, reactor L/D ratio, solids residence time, to consistently achieve the DRI quality, determination of fluidization factor (*f*) to ensure proper gas velocities and distribution through the solids bed, among others for the proper gas distribution and design of the process and equipment for H₂ utilization.

These campaigns at demonstration/pilot plant tests with high-H₂ sustain the fact that the ENERGIRON technology is already available for the use of 100% H₂ when needed. All 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.

The trend for H₂-based steelmaking

In general, Europe is leading the trend towards the intensive use of H₂ 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. Specific future aspects of ESTEP will cover issues related to H₂ supply, use and transport as well as energy storage in general. Some projects oriented on this target are:

- ThyssenKrupp with the Carbon2Chem® Project aiming at using CO₂ emissions from steelworks and surplus energy from renewable sources for chemical production.

- Voestalpine, Siemens and Verbund for the H2FUTURE Project, building a pilot facility for green H₂ at Linz.
- SSAB, LKAB and Vattenfal with the HYBRIT initiative, based on H₂ for steel production.
- Salzgitter for the SALCOS project study 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.

In 2016, HYBRIT was established with the aim to replace coking coal, traditionally needed for ore-based steelmaking, with hydrogen, a fossil-free steelmaking technology, with virtually no carbon footprint. HYBRIT set a specific target toward the construction and operation of a pilot plant with the aim to test hydrogen as a reducing agent in the production of Direct Reduced Iron (DRI).

Tenova was contracted by HYBRIT to supply its DRI solution for the world’s first fossil-free steelmaking technology with virtually no carbon footprint in Sweden.

Thanks to the unique characteristics of its process and its specific expertise in direct reduction with high content of H₂, Tenova HYL was the perfect fit with the HYBRIT project. The Tenova company based in Mexico was chosen also thanks to the maneuverability of the production of DRI, adding unique flexibility in terms of operations. Moreover, the experience gained over nearly 60 years of DR technology development and the references of more than 40 DR modules in operation makes Tenova HYL a reliable partner for this innovative process. The pilot plant will be located in Luleå, Sweden, and is expected to begin operations in 2020.

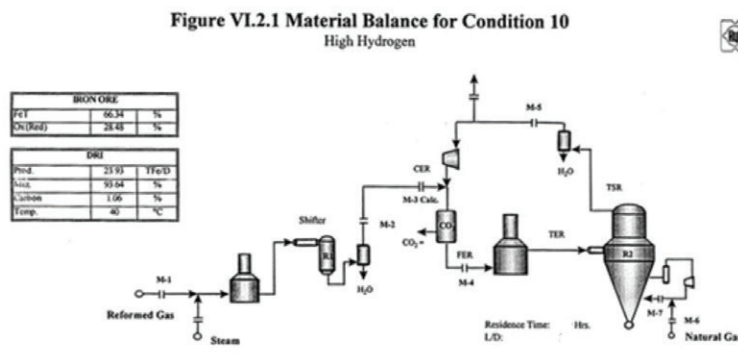


Figure 4. HYL Pilot Plant tests campaigns with ≥90% (vol.) H₂

The SALCOS (Salzgitter Low CO₂ Steelmaking) project, a study initiated by Salzgitter AG together with Tenova and Fraunhofer-Gesellschaft (FhG) in 2015, is addressed to analyze 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.

As one of the major results, the SALCOS study could demonstrate the possibility to follow stricter CO₂ 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, including H₂ use, reduces the environmental impact in terms of CO₂ emissions up to around 95% depending on framework conditions. This stepwise transformation process requires considerable investments in new plant equipment adjustments to comply with the given regulatory and economic framework and to avoid unreasonable OPEX increase, for instance due to taxes on electrical energy (EEG allocation). These conditions have to be adapted first in order to facilitate the realization of the transformation project.

Challenge while melting H₂-based DRI in EAF

EAF's operations to melt DRI are based on certain DRI characteristics for reducing the remaining FeO and promoting foaming slag. The optimum %C in DRI is based on the amount of DRI in the mix feedstock for a 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 feeding low or 0%C DRI, which will require particular EAF melting practices. Fact: a minimum carbon content in DRI or carbon injected separately is required for EAF steel production operations.

Options:

- 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 the 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/tLS, 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/tLS, option 2) will represent just about 50 kg CO₂/tLS.

In terms of overall decarbonisation, Option 2) would be the preferred choice for H₂-based steelmaking.

Economics for H₂-based ironmaking

In terms of OPEX, producing hydrogen by water electrolysis implies a direct cost of the connection to the power grid. Considering ~4.0 kWh/Nm³ H₂, the energy consumption for DRI, based on the ENERGIRON ZR technology, will be ~3.08 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 cost is of a high level. Currently, for example, in Germany the power from renewable sources has dropped to below €0.05/kW, 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 emission targets, with corresponding credits, shall be taken also into account in the cost equation.

According to IRENA (International Renewable Energy Agency), Renewable Power Generation Costs in 2017, 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 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 can undercut fossil fuel-fired electricity generation, without financial support.

To be on a competitive scenario in terms of green H₂-based DRI production, as per current electrolysers efficiency and without CO₂ credits, the electricity from renewable sources should be ≤ \$0.02 /kWh. The required CAPEX is also an important issue to be

significantly reduced. This may be possible within the coming years.

Remarks

In summary, the current status for intensive use of H₂ is as follows:

- Hydrogen use with up to ~70% vol. has been used at industrial scale in HYL/ENERGIRON plants with external reformer of NG since six decades ago.
- Extensive demonstration plant tests were carried out during the 1990s by Tenova HYL, defining the process and plant design parameters for the scheme with >90% H₂. Therefore, the most suitable and proven DR technology for 100% H₂ is available.
- Decarbonisation via H₂ use in the steelmaking industry is already under development in Europe through various projects under the ESTEP umbrella. Others will follow in the next future.
- Salzgitter AG, together with Tenova and Fraunhofer-Gesellschaft (FhG), has initiated the study of the SALCOS project for stepwise conversion of the integrated BF-BOF installation to DR-EAF and H₂ use for reduction of about 95% CO₂ emissions.
- Due to the unique characteristics of its process and its specific expertise in direct reduction with high content of H₂, Tenova HYL has been selected to supply the pilot plant technology for the HYBRIT project with hydrogen, a fossil-free steel-making technology.
- Improved efficiency of electrolysers for H₂ generation along with expected low cost electricity from renewable sources will make feasible the fossil-free ironmaking route based on DRI production in the coming years.

TENOVA CONTRACTED BY HYBRIT DEVELOPMENT

Hybrit Development chose Tenova DRI solution to develop the world's first fossil-free steelmaking technology with virtually no carbon footprint.

Hybrit Development selected Tenova, a company of the Techint Group specialized in innovative solutions for the metals and mining industries, as supplier of selected process equipment, for direct reduction ironmaking, for its pilot plant for fossil-free steel in Luleå, Sweden.

In 2016, the HYBRIT Initiative for fossil-free steelmaking was established with the aim of replacing coking coal, traditionally needed for ore-based steelmaking, with hydrogen in order to obtain a fossil-free steelmaking process route with virtually no carbon footprint. The HYBRIT Initiative set a specific target toward the construction and operation of a pilot plant with the aim to test hydrogen as reducing agent in the production of Direct Reduced Iron (DRI).

"I am particularly excited and proud of being part of this project", stated Stefano Maggiolino, Tenova HYL CEO. "Tenova puts innovation, safety and sustainability at the core of its technological innovations and products and Tenova HYL represents the state of the art in DR plants design, reliable operation, environmental friendliness and economy".

"Tenova HYL, which has a long tradition of supplying industrial plants for DRI production, will supply selected process key equipment for Direct Reduction Ironmaking. By using state-of-the-art production technology as a starting

point, we will more quickly reach our goal of a fossil-free future", said Mårten Görnerup, CEO of Hybrit Development AB."

The pilot plant is designed to develop production of DRI using Hydrogen, a crucial process step in the future fossil-free steelmaking production route. The pilot plant will be located in Luleå, Sweden, and is expected to begin operations in 2020.



Pilot plant in Monterrey, México (1977)

TERNIUM MEXICO 4M DR PLANT MARKS 20TH ANNIVERSARY

A LANDMARK OF INNOVATION IN THE IRONMAKING INDUSTRY CELEBRATES ITS 20TH YEAR OF OPERATION IN 2018.

Ternium's 4M Direct Reduction Plant; built on a brown field, was conceptualized as a bold innovation statement in the steelmaking world. This project marked a number of "firsts" in the industry – first Zero Reformer industrial scale facility, first Pneumatic Transport System at industrial scale, first EAF to use a continuous feed of Hot DRI, first EAF to use Hot DRI with High-carbon content – among others, that were taken up as challenges and opportunities by a tireless team of Mexican entrepreneurs and engineers.

1998: a year when the world was still dealing with Lady Diana's passing, struggling with Max Martin's creations on the music charts and reading the "1998 fatwā"... but also a year of great global events, like the founding of a little-known company called Google, the birth of the Euro, the startup of the construction of the International Space Station (ISS) and the signing of the Belfast Agreement. So, it was a good year to create and innovate and therefore we like to consider the startup of Ternium's 4M Plant part of the latter.



20 years of Success

At a time when the natural gas prices in México reached values as high as 12 USD/mmBTU and the scrap market had its normal fluctuations, it became essential to attain the ability to produce quality steel products in an efficient way. The assembly of a mini-mill (DRI-EAF) looked like a way forward, because not only would the efficiency of the Zero reformer process come in handy to reach the objective, but also the possibility of feeding hot DRI directly to an EAF followed by an in-line processing and finishing of the steel loomed large as an opportunity for a steelmaker to improve efficiency on their production line. Now, add to that the fact that in this case the iron ore came from a concession of a mine located in southwest México.

Also by that year, the use of continuous casting and the trends in thin-slab, thin-strip and near net-shape casting had allowed steel mills to enter into new and more demanding steel products segments. So, having a source of pure iron units free of tramp elements and impurities sounded like a smart investment.



20 years later we can conclude it was, as the integrated mini-mill model has become one of the most efficient steel production routes, and the EAF continues to increase its share of the world crude steel production. Also the benefits of operating an EAF using high amounts of hot DRI (80-90%) with a carbon content of 3.5 – 4.5 %, combined with scrap have been demonstrated, setting a benchmark worldwide and helping the development of this type of projects.

Another very important aspect of the technological evolution of the 4M DR Plant is its environmentally friendly design. This plant has two CO₂ removal units, one of which (the chemical absorption unit) allows the commercialization of the CO₂ generated as by-product in the reduction process. As Tenova HYL continues to work on the Next Big Thing, the 4M DRI-based mini-mill continues to be the benchmark for the steelmaking world.

+17,500,000	
Tons of DRI produced	
94% Avg. Metallization	
Avg. Carbon Content 3.8%	
Avg. Consumptions	1.37 t of oxide
	2.30 t DRI
	Gcal
	t DRI

CALENDAR OF EVENTS

December 2018 - April 2019

Look for Tenova HYL at the following events:

- December 10 - 12
Fast Markets MB – MEIS 2018
Park Hyatt Dubai Creek
Dubai, UAE
- February 12-14
24th Mexican Steel Forum
Sheraton Ambassador Hotel
Monterrey, México

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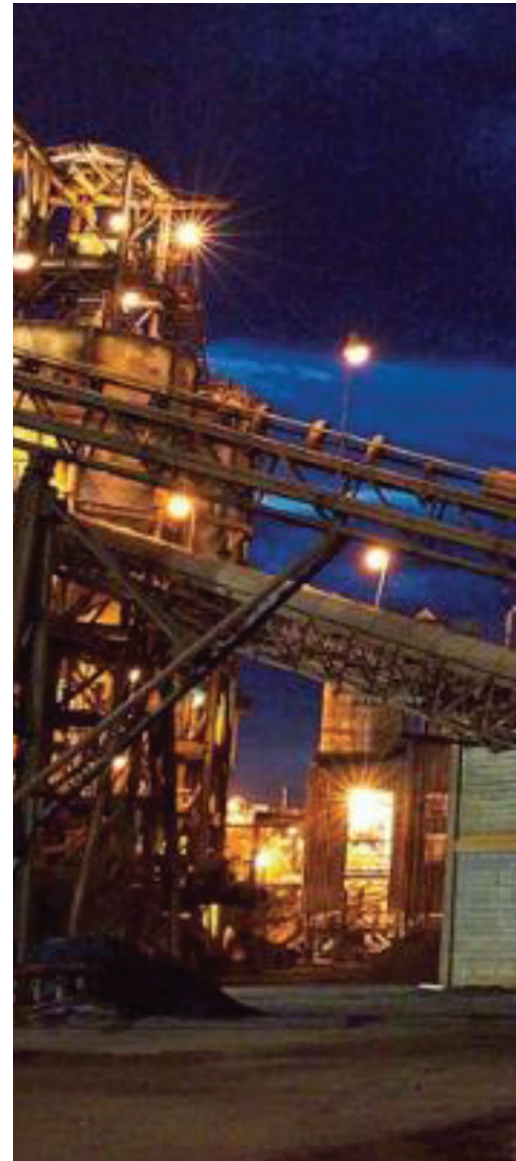
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