# Introduction to direct reduction technology and outlook for its use

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The gas-based direct reduction technology is the process used to convert iron ore, either in the form of pellets or lumps, into metallic iron by means of reducing gases and without the need of melting. This technology was born in the early 50s in Mexico and has experienced increasing popularity due to the properties of the final product, commonly called Direct Reduced Iron (DRI), as virgin source for high quality steel production through electrical steelmaking, as an alternative to low residual scrap. In addition, the reduced environmental footprint compared to the traditional integrated route (blast furnace coupled with basic oxygen furnace) makes the direct reduction the most promising alternative for iron production in countries where very restrictive regulations on emissions are applied, with, for example, the possibility to capture and commercialize the CO<sub>2</sub> as by-product. The use of DRI can be also effective in decreasing emissions in existing plants. Its addition directly in the BF/BOF burden allows to increase productivity and to decrease emissions by reducing significantly coke and sinter consumption. Latest installations of new direct reduction plants are returning remarkable results in term of product quality and integration with steelmaking.

KEYWORDS: DIRECT REDUCTION TECHNOLOGY - DRI - GHG EMISSIONS - CO2 REMOVAL

### INTRODUCTION

The performance requirements for modern steelmaking facilities are becoming more and more stringent, as customers and markets are continuously pushing for technologies having high quality steel, produced with profitability and small environmental footprint at the same time.

The blast furnace coupled with basic oxygen furnace (BF-BOF), using directly iron ore as raw material for steel production, is for sure a chance for producing high grade steel. Nevertheless, using

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On the contrary, EAF steel production using scrap is significantly less impacting and the environmental parameters are more easily respected. Nevertheless, due to unstable scrap availability and quality (market fluctuations and residual elements), price and grade of the final steel are less competitive. For this reason, the ironmaking operators intensified the search for alternative raw material for the EAF.

The Direct Reduced Iron (DRI) is a valuable alternative to the high quality scrap shortage in both emerging and developed countries. Using DRI as feed for the EAF, mills can produce the superior steel grades demanded by such users as automotive, special and tool steels that were originally only possible in integrated mills with BF-BOF. The DRI is obtained chemically by reducing the iron oxide to metallic iron without the melting of the product. It is generally round shaped, with a diameter in the range 5-18 mm. As alternative, when compacted by compression in 110x50x30 mm briquette shape, it is called HBI (Hot Briquetted Iron). Main characteristics of this product are the high purity, the high level of metallization (up to 96%) and the transportability over long distance.

## Direct reduction



**Fig.1** - Direct reduced iron (a) having typical diameter of 5-18 mm. Hot briquetted iron (HBI) (b) having typical dimensions of 110x50x30 mm.

Industrially begun in late '50 in Mexico with HYL process, the DRI production has reached up to date about 74 MTPY, covering the 4% of the world requirement for steel production. The most part comes from the gas-based (typically natural gas) direct reduction technologies and it is mainly located in MENA, Americas and Russia. The DRI offer is going to increase considerably in the next years. Close to 16 MTPY new capacity is going to be installed, with the forecast for doubling the total capacity within 2030.



Fig. 2 - Main process routes for world steel production in 2012 [1].



Fig. 3 - DRI production trend from 1980 to 2014 [2].

As far as the quality is concerned, the DR-EAF route is certainly not limited to producing simply commercial steel grades. Adding to this the ability to produce DRI in capacities exceeding 2 million tons per year and coupling this type of plant with a modern EAFbased meltshop, a new type of "integrated" mill for the near future is available: a high volume, integrated DR-EAF mill, capable of competing in both quality and cost with the traditional one.

### DIRECT REDUCTION PROCESS DESCRIPTION

Several direct reduction technologies have been developed, but only a handful has been established commercially. Among these, Energiron Zero Reformer (Energiron ZR) process configuration is here described as an example for the appreciated characteristics in increasing the productivity and improving the efficiency of direct reduction plants, while minimizing the environmental impact. The plant is designed to convert iron ore, either in pellets or lumps, into metallic iron using reducing gases in the direction opposite the solid material flow inside a moving bed shaft furnace.



Fig. 4 - Energiron ZR process scheme.

The natural gas is used as a make up in the reduction circuit. It is injected in the process gas circuit and mixed up with the recycled reducing gas. The mixture is passed through the process gas

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heater to get most of the temperature required and then oxygen is injected in the transfer line just before the reactor in order to increase the temperature of the reducing gas to the required level for in-situ reforming and reduction inside the reactor. The partial oxidation and pre-reforming reactions of natural gas with oxygen are carried out in the transfer line. In this way, reducing gases (H<sub>2</sub> and CO) are produced. Once in contact with the solid material inside the reactor, further cracking and reforming reactions are carried out due to the catalytic effect of metallic iron. These partial oxidation and reforming reactions are the following:

$$CH_4 + \frac{1}{2}O_2 \longrightarrow CO + 2H_2 \tag{1}$$

$$O_2 + 2H_2 \longrightarrow 2H_2O$$
 (2)

$$CH_4 + H_20 \longrightarrow CO + 3H_2$$
 (3)

$$CO_2 + H_2 \longrightarrow CO + H_2O$$
 (4)

The oxygen is removed from the iron ore by chemical reactions based on hydrogen ( $H_2$ ) and carbon monoxide (CO) for the production of highly metallized DRI. The overall reduction reactions are reported here below.

$$Fe_2O_3 + 3H_2 \longrightarrow 2Fe + 3H_2O$$
 (5)

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$
 (6)

The basic ZR scheme permits the direct use of natural gas. Anyway, also the use of conventional steam-natural gas reforming equipment as an external source of reducing gases, which has long characterized the process, is possible. Other reducing agents such as hydrogen, syngas produced from coal or oil gasification systems, pet coke and similar fossil fuels, and cokeoven gas, among others, are also potential sources of reducing gas, depending on the particular situation and availability. In any case, the same basic process scheme is used regardless of the reducing gas source.

Normally, a wide variety of iron ores can be used with no difficulty in the reduction 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 m<sup>2</sup> 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, thus minimizing dust losses through top gas carry-over. This lowers the overall iron ore consumption, which in turn lowers the overall operating costs. Additionally, the practice of coating the pellets with a thin layer of cement or lime, before charging them into the shaft furnace, prevents the sticking problems and also contributes to reducing fines generation in the reduction process. Nevertheless, in particular when the feed mix includes significant amounts of iron ore pellets with a low compression strength number (such as for example BF grade pellet or lump) fines generation could be significant [3].

The process scheme is characterized by the selective elimination

of both by-products of the reduction process:  $H_2O$  and  $CO_2$ . Particularly, the selective elimination of  $CO_2$  through chemical absorption is highly efficient and low energy consuming due to the high operation pressure of the plant. The  $CO_2$  selectively removed from the process gas stream can be used for other applications or sequestrated.

A distinct advantage of this process scheme without an integrated reformer is the wider flexibility for DRI carburization. DRI carbon levels up to 5% can be obtained, due to the prevailing conditions of high methane (CH<sub>4</sub>) concentration within H<sub>2</sub>-CO and the high temperature of the bed (>860°C), which favors the diffusion of Carbon into the Iron matrix and the precipitation of Iron Carbide (Fe<sub>3</sub>C). The presence of the iron carbide in the EAF charge is not only an additional source of energy for the melting but, compared with carbon injection, it gives benefits in terms of foaming slag, continuous feeding and yield. DRI with high content of C in the form of Iron Carbide is also more stable and less reactive compared to a low Carbon DRI (< 3%), allowing an easier and safer storage / handling.

The integration of the direct reduction plant with the EAF by means of the patented HYTEMP system also increase the process yield, for the reason that all the fines are completely recovered in the EAF, which is designed to minimize the losses through the fumes. The HYTEMP is basically a pneumatic system used to transport the hot material discharged at a temperature above 600°C directly to the EAF by means of a carrier gas compatible with the hot DRI (i.e.: nitrogen) so that its guality is maintained. In this way, all the thermal energy of the hot discharged DRI is recovered and immediate benefits can be seen at the meltshop, in terms of electrical consumption saving and reduced tap-to-tap time. For example, when DRI with a temperature of 600°C is melted in the EAF, the savings in power are up to 140 kWh/t<sub>i</sub> with an increase in productivity of up to 22% for a practice of 90% hot-10% cold DRI if compared with a charge of 95% cold DRI and 5% scrap.

An external DRI cooler is also installed in order to cool down the hot DRI when the meltshop is not available, thus always ensuring continuous, smooth operation of the DR Plant for 8,000 hours per year.



Fig. 5 - HYTEMP System Flow Diagram.

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### **OVERALL ANALYSIS FOR CO, EMISSIONS**

By the point of view of the environmental footprint, the total emissions due to the DRP-EAF route are dramatically lower compared to the alternative route BF-BOF. The steel making industry is characterized by an intensive use of fossil fuels, which leads to a significant impact to the environment through Global-Warming-Greenhouse Gases (GHG), mainly in the form of CO, emissions. Regarding GHG emissions, the EU has committed to three targets for 2020. The first is to reduce emissions by 20% on 1990 levels. The second is to provide 20% of its total energy from renewables. The third is to increase energy efficiency by 20% from 2007 levels. For the traditional integrated steelmaking, the primary energy source for reduction of iron oxides is coal, while for the DRP-EAF route, as already detailed, the sources can be different. In general, just based on the use of coal in the BF-BOF route as compared with NG in the case of DR-EAF route, by simple material balance, the DR-EAF route emits 40-60% less CO<sub>2</sub> (depending on plant location due to source of power generation) [4].

As reported in previous works [4][5], typical energy balance for an integrated steel works is presented in Figure 6. This facility comprises a coke oven plant/sinter plant, a blast furnace for the generation of the hot metal (HM), a BOF steel plant with ladle furnace and a thin slab caster or compact strip plant (CSP) for the production of hot rolled coils (HRC). The major gaseous fuel by-products, which are recovered in integrated steel works, are: blast furnace gases (BFG), coke oven gases (COG) and basic oxygen furnace gases (BOFG). Energy balances of integrated steel works show that most of the gaseous energies are mainly used either for power generation or else flared. As only a minor part of the electrical power that could be generated from these gases can be used in the steel works for its own requirements, most of the electrical power has to be exported.



### Fig. 6 - Energy balance in an integrated BF-BOF based steelmaking facility.

It should also be noted that the optimized utilization of primary fossil energy has the effect of significantly reducing the specific CO<sub>2</sub> emissions per tonne of HRC. For this optimized scheme, the specific CO<sub>2</sub> emission in flue gases via the conventional BF-BOF route is about 1,7 tonnes of CO<sub>2</sub>/t<sub>HRC</sub>.

On the other hand, the DRP-EAF route based on natural gas is presented in Figure 7. The direct reduction plant was selected

for high-C DRI production as 100% feed to the EAF. We can observe that while the integrated steel plant is a net exporter of electricity, the DRP-EAF mill is an importer. Also, more than half of the gaseous  $CO_2$  is selectively removed, a strong potential for alternate disposal of this by-product, thus significantly reducing GHG emissions. Electricity generation has an impact on  $CO_2$  emissions, depending on the location of the steel plant.





As mentioned above, the Energiron ZR scheme has the flexibility of using reducing gases from different sources (NG, Syngas, COG). The basic process configuration is unchanged for any energy source application.

The scenario of a DRP-EAF steelmaking configuration when using COG as reducing gas is presented in Figure 8. The compression of COG is required to feed the DR plant and this is reflected in higher power consumption.

For this particular case, just as reference, cold DRI has been considered as feed to EAF, while in case of hot DRI charging, the power consumption in EAF will be the same as the previous case.



**Fig. 8** - Energy balance in a DRP-EAF based steelmaking facility, using COG and producing cold DRI (CO<sub>2</sub> emissions related to power consumption and iron ore production are considered separately).

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As reference, the following Table I below show the comparison between both routes in terms of overall  $CO_2$  emissions, from iron ore production to final HRC, for a country where power

generation is characterized by 0,4 kg  $\rm CO_2/kWh$  (approx. the reference value for Italy – Source: ISPRA).

Tab. 1 - CO, emissions: DRF	-EAF vs. BF-BOF	comparative analysis
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Com parative analysis: CO <sub>2</sub> Emissions / tonne of HRC						
Scenario for electricity source	DRP-EAF route vs. BF-BOF route (location: 0,4 kg CO <sub>2</sub> /kW h)					
Route	DRP ZR Plant-EAF Natural Gas Hot DRI	DRP ZR Plant-EAF COG Cold DRI	BF-BOF Hot Metal			
	kg CO <sub>2</sub> / t HRC	kg CO <sub>2</sub> / t HRC	kg CO <sub>2</sub> / t HRC			
Iron ore (production) + fluxes	111	111	119			
$CO_2$ in flue gases + removal system	533	396	1695			
Total effective on site emissions	644	507	1814			
$\rm CO_2$ generation due to power requirements	259	370	-139			
Total balance (including power requirements)	903	877	1675			
% Reduction of CO <sub>2</sub> Emissions	46%	48%	0%			
If disposal of selective $CO_2$ removal (ZR scheme)	633	607	1675			
If disposal of selective $CO_2$ removal (% Reduction of $CO_2$ emissions)	62%	64%	0%			

Although the BF-BOF route has a small advantage due to the significant export power, the DRP-EAF route based on NG or COG presents higher advantages in terms of overall energy consumption and related CO<sub>2</sub> emissions.

In general, when comparing both the routes:

- The conversion of CH<sub>4</sub> → CO + 2H<sub>2</sub> for reduction of ore drastically reduces CO<sub>2</sub> in site emissions as compared to coal, for which case, all reductant are coming from C.
- Even with the credit from power export in the BF-BOF route, electricity sourcing has an impact on CO<sub>2</sub> emissions as noted in Table 1, there is a wide gap in terms of specific CO<sub>2</sub> emissions between the two routes.
- In a location with power generation involving 0,4 kg CO<sub>2</sub>/ kWh, there is a decrease of about 45-50% CO<sub>2</sub> emissions through the DRP-EAF route.

It is clear that there is an implicit difference in terms of CO<sub>2</sub> emissions between BF-BOF and DRP-EAF routes simply because of the nature of the primary energy being used. However, there is an important difference between DR processes as well. While some DR processes simply vent non-selective CO<sub>2</sub> through the flue gases, the Energiron process based DR plants selectively remove the CO<sub>2</sub>, which can be and is actually used for commercial applications or else sequestrated.



**Fig. 9** - Non-selective CO<sub>2</sub> emissions (through flue gases) of different steelmaking routes.

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In addition to the EAF, the DRI produced can also be used for a) feeding the BF to increase HM productivity and/or decrease coke/ PCI rate, b) feeding the BOF replacing scrap as coolant agent. So, an all-around integration with the BF-BOF can be obtained, giving significant benefits by the point of view of both energy efficiency and environmental impact.



**Fig. 10** - Example of direct process integration with blast furnace technology. The addition of DRI/HBI in the blast furnace feed can be used in order to decrease the total  $CO_2$  emission of the traditional integrated plants without affecting the site productivity.

The case of DRI/HBI charging in the BF has been deeply investigated [6]. DRI in the BF process is under specific conditions a tool for optimizing the BF operations. It has been verified that the addition of 7/15% of HBI in the BF burden allow to increase the productivity by the same rate, while decreasing the coke requirement by about 25-30 kg/t<sub>HM</sub>. In alternative, it is possible to use the HBI addition in order to keep the same productivity but decreasing the CO<sub>2</sub> emission up to 20%. The addition of DRI/HBI in the BF burden has been identified as one of the most viable solution to decrease the CO<sub>2</sub> emissions in the traditional integrated plants, operating in countries where emissions threshold is impossible to be matched with the typical feed.

### WASTES AND BY-PRODUCTS

Iron ore based steelmaking accounts for about 75% of world steel production, with the balance being from scrap recycling. The main inputs are: iron ore, coal, and limestone, among others. The main by-products are slag (about 90%), sludge and dusts. On average (Fig. 11), in the BF-BOF route the amount of these by-products exceeds 400 kg/t crude steel while for the DR-EAF route it is less than 200 kg/t crude steel. Slag is made up of mixtures of silica, calcium and magnesium oxides, and aluminum and iron oxides, as by-products coming from slagging and fluxes being used during the steelmaking process.



Fig. 11 - Main by-products by steelmaking routes (Source: World Steel Association. Steel Industry By-products. Feb. 2012).

On the other hand, additional effluents from the BF-BOF route are related to the use of coal as the primary energy source: BTX (light oil vapor), Tar vapors, naphthalene vapor, ammonia gas, hydrogen sulfide gas and hydrogen cyanide gas; all of which require specific and special treatment. The COG is normally used as fuel at the coking battery and steel works; flushing liquor is recirculated to the coke oven plant, waste water is discharged to treatment plant; ammonia/ammonia sulfate is sold as byproduct and light oil (if recovered) is also sold as by-product and sulfur/sulfuric acid (if gas is desulfurized), is sold as by-product. All these make the emissions treatment a very intensive and expensive system of the integrated steelmaking plant and which ultimately is reflected in higher CAPEX and OPEX requirements. The summary of emissions from BF-BOF vs DR-EAF route has been reported as per Table 2. The main impact in terms of NO<sub>x</sub> and SO<sub>2</sub> emissions are an order of magnitude higher for the BF-BOF route, as well as the higher metals emissions from the integrated route. (Note: in the table, no credit due to electricity co-generation from the integrated route is reflected in CO<sub>2</sub> emissions).

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	BF/BOF	EAF	DRI
Energy consumption (GJ/t)	22	5.8	10
$CO_2$ eq emissions (t $CO_2$ eq/t)	2.1	0.7	0.4
Water consumption (m <sup>3</sup> /t)	2.6	0.6	0.8
Land use $(m^2/t)$	1.7	0.5	0.4
Emissions to air (kg/t)			
NOx	1	0.04	0.2
SO <sub>2</sub>	1	7.4 x 10 <sup>-4</sup>	
CO	56	9.8	
PM <sub>10</sub>	0.15	0.14	0.13
PM <sub>25</sub>	1.4 x 10 <sup>-2</sup>	0.3 x 10 <sup>-2</sup>	7.7 x 10 <sup>-2</sup>
Pb	2.6 x 10 <sup>-4</sup>	$1.4 \ge 10^{-4}$	
Hg	9.8 x 10 <sup>-6</sup>	0.1 x 10 <sup>-6</sup>	
As	6.2 x 10 <sup>-6</sup>	6.6 x 10 <sup>-6</sup>	
Cr <sup>6+</sup>	4.5 x 10 <sup>-6</sup>		
Ni	3.5 x 10 <sup>-5</sup>	1.6 x 10 <sup>-5</sup>	
Cd	8.1 x 10 <sup>-6</sup>	0.5 x 10 <sup>-6</sup>	

Tab. 2 -	Main emissions by	y steelmaking routes	(Source: Defining	sustainability	indicators	of iron
	and	steel production. V. S	Strevoz, A. Evans, T	T. Evans).		

### CONCLUSIONS

The new COP21 agreement signed in Paris in December 2015 is a strong message of how it is no more possible to postpone the GHG emission decreasing. At the same time, the even more strict requirements for high-end steel applications drive the steelmakers to search for competitive virgin iron sources. For these specific and important target issues, direct reduction technology offers the unique option available on the market for production of DRI, the purest form of iron, while limiting the  $CO_2$  and others emissions compared to the traditional BF-BOF route. Moreover, the Energiron DR process intrinsically include a  $CO_2$  absorption system for the selective sequestration of this by-product.

This is achieved without the need of additional thermal or electrical energy, which eventually will imply further direct and/ or indirect non-selective  $CO_2$  emissions. So, it is reasonable to expect that, in the next future, the direct reduction technology will concur ever more to the world steel production.

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