Achieving Carbon Free Emissions via the ENERGIRON DR Process

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INTRODUCTION

For more than 50 years Tenova HYL has developed technologies designed to improve DRI based steelmaking competitiveness and productivity. The recent alliance between Tenova HYL, Techint and Danieli brings a new brand - ENERGIRON - to the forefront of the direct reduction industry. The ENERGIRON process has been improved over generations and the current status of the technology, the ENERGIRON ZR (or Self-reforming) Process, was developed to allow reduction of iron ores in a shaft reactor without external gas reforming equipment. This process scheme has the ability to produce high carbon DRI, which allows producers to obtain maximum benefits of carbon in the steel making process while producing a product of higher stability. The HYTEMP® System developed to transport hot, high carbon DRI directly to the EAF meltshop, has been successfully operating since 1998, now in full operation in the 1.6 million t/y Emirates Steel plant in Abu Dhabi, continuously transporting more than 200 t/h of hot DRI to the meltshop. The ultimate objective has been the optimization of overall energy consumption, with the implicit reduction of CO_2 emissions.

ENERGIRON technology is characterized by its flexible reformerless process configuration which is able to satisfy and exceed the current stringent environmental requirements worldwide. The gaseous and water effluents of the process are not only low but easily controlled. Incorporation of selective carbon dioxide (CO_2) removal systems has been a key factor over the past decade in significantly reducing the emissions levels, providing an additional source of revenue for the plant operator via the captured CO_2. This paper focuses on the environmental aspects related to greenhouse gases emissions and specifically on the unique patented scheme to selectively and efficiently remove about 90% of total CO_2 from the DR plant.

CO_2 EMISSIONS IN STEELMAKING

The steelmaking 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_2 emissions. For the integrated steelmaking process, the primary energy source for reduction of iron oxides is coal, while for the DR-EAF route, the source of reducing gases can be not only natural gas (NG) but also coal itself through the use of gases from coal gasification (Syngas) or coke oven gas (COG). In general, just based on the use of coal in the BF-BOF route as compared with NG in the case of the DR-EAF route, by simple material balance, the DR-EAF route emits 40% - 60% less CO_2 (depending on plant location due to source of power generation) as compared to the BF-BOF route.

A typical energy balance for an integrated steel works is presented in Figure 1. This facility comprises a coke oven plant/sinter plant and blast furnace for generation of hot metal (HM) and a BOF steel plant with ladle furnace and thin slab caster or compact strip plant (CSP) for the production of hot rolled coals (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 steelworks for its own requirements, most of the electrical power has to be exported. It should also be noted that the optimized utilization of primary fossil energy also has the effect of significantly reducing the specific CO_2 emissions per tonne of HRC. For this optimized scheme, the specific CO_2 emission in flue gases via the conventional BF/BOF route is about 1.6 tonnes of CO_2/t HRC.

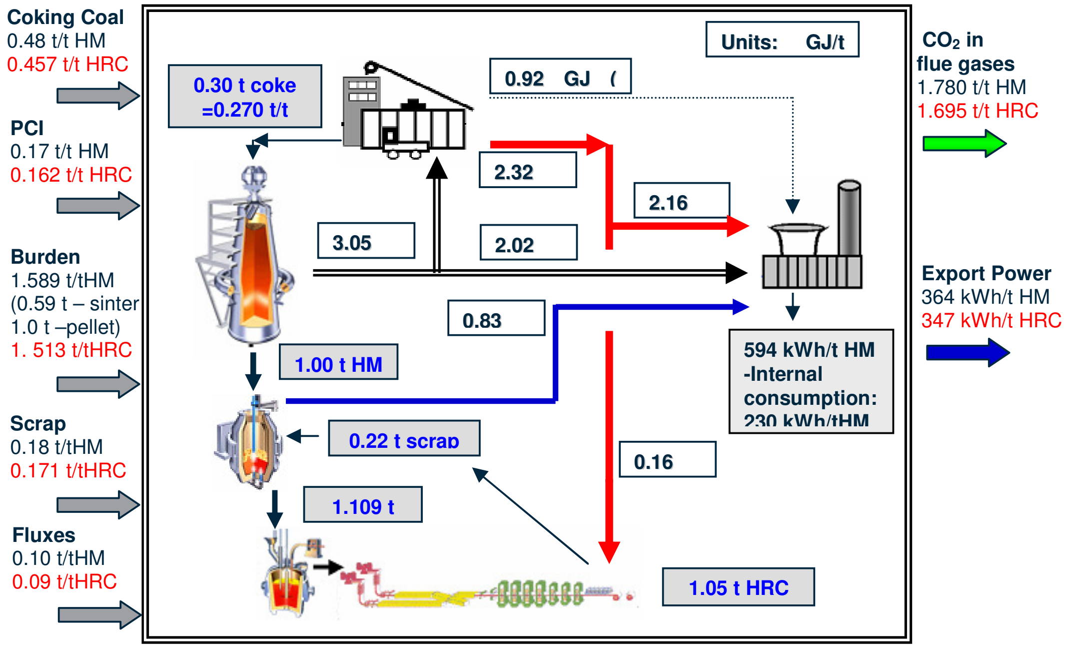

Figure 1. Energy balance in an integrated BF-BOF based steelmaking facility

On the other hand, the DR-EAF route is presented in Figure 2. The ENERGIRON ZR-based DR plant was selected for high-C DRI production as 100% feed to the EAF.

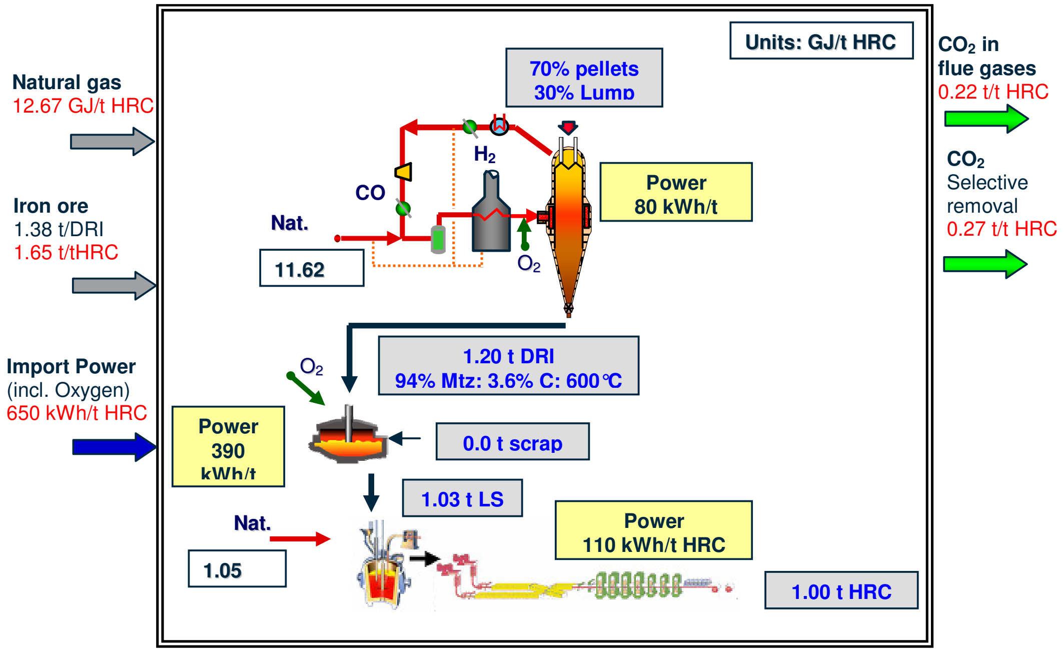

Figure 2. Energy balance in a DR-EAF based steelmaking facility

We can observe that the while the integrated steel plant is a net exporter of electricity, the DR-EAF mill is an importer. By using the ZR scheme, more than half of the gaseous CO_2 is selectively removed; this is a strong potential for alternate disposal of this CO_2, thus significantly reducing the GHG emissions. Electricity generation has an impact on CO_2 emissions, depending on the location of the steel plant.

Electricity generation is a composite of sourcing from natural gas, coal, hydraulic, eolic, nuclear, biomass, and depending on the particular location, the CO_2 emission is a reflection of the overall combination. There are countries like Venezuela where the power generation is based on 0.3 kg CO_2/kWh and others like India, where it is of 0.9 kg CO_2/kWh.

As reference, the following Table I show the comparison between both routes in terms of overall CO2 emissions, from iron ore production to final HRC, for a country where power generation is characterized by 0.74 kg CO_2/kWh.

Comparative Analysis: CO_2 Emissions / tonne of HRC		
	DR-EAF route vs. BF-BOF route (location: 0.74 kg CO_2/kWh)	
Route	**DR ZR Plant-EAF**	**BF-BOF**
	kg CO_2/t HRC	**kg CO_2/t HRC**
Iron ore (production) + fluxes	129	119
CO_2 in flue gases + removal system	461	1695
Subtotal	**590**	**1814**
Power requirements	394	-257
Total	**984**	**1557**

Table I: CO_2 Emissions: DR-EAF vs. BF-BOF comparative analysis

In general, when comparing both routes:

- The conversion of $CH4 \rightarrow CO + 2H_2$ for reduction of ores, drastically reduces CO_2 emissions as compared to coal, for which case, all reductants are coming from C.

- Even with the credit from power export in the BF-BOF route, electricity sourcing has a significant impact on CO_2 emissions as noted in Table I, where two completely different scenarios are compared.

- In a location with power generation involving 0.74 kg CO_2/kWh, there is a decrease of about 40% less CO_2 emissions through the DR-EAF route.

It is clear that there is an implicit difference in terms of CO2 emissions between BF-BOF and DR-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_2 through the flue gases, the ENERGIRON process-based DR plants selectively remove CO_2, which can be and is actually being used for commercial applications or else sequestrated.

THE CARBON BALANCE IN THE DR PLANT

For gas-based DR process, the energy source for reduction of iron oxides is made up of hydrocarbons and/or carbonaceous compounds.

- For the case of natural gas (NG), the hydrocarbons are converted through external or "in-situ" reforming to the required reducing gases H_2 and CO:

  $CH_4 + H_2O \rightarrow CO + 3H_2$

  $CH_4 + CO_2 \rightarrow 2CO + 2H_2$

- In the case of gases from coal gasification (Syngas), coal is gasified to produce, among others, the same reducing gases:

  $C + 1/2\ O_2 \rightarrow CO$

  $C + H_2O \rightarrow H_2 + CO$

  $C + 2H_2 \rightarrow CH_4$

  $CO + H_2O \rightarrow H_2 + CO_2$

- In the case of direct use of coke oven gas (COG), the make-up gas presents similar carbonaceous analysis in a different proportion:

  55-64% H_2; 8-10% CO; 3-4% CO_2; 20-25% CH_4; balance others

At the end, the reducing gas make-up to the DR plant is a feed of Carbon. Regardless of the DR process configuration, from the total Carbon input to the DR plant, only 10-25% (depending on the Carbon content in the DRI) exits the process as combined Carbon in the DRI. By the principle of mass conservation, the balance must leave the process, which for the DR process, is in the gaseous form as CO_2.

Taking as an example the use of NG as the source of reducing gases for a DR plant, typical energy consumption is about 2.30 Gcal/t DRI. As shown in Figure 3, for a typical NG analysis, the total carbon associated to this energy input is about 140 kg C/t DRI. Depending on the process scheme, the carbon associated with the DRI output is just 20-35 kg/t DRI. Thus 105-120 kg C/t DRI is emitted from the DR plant as CO_2.

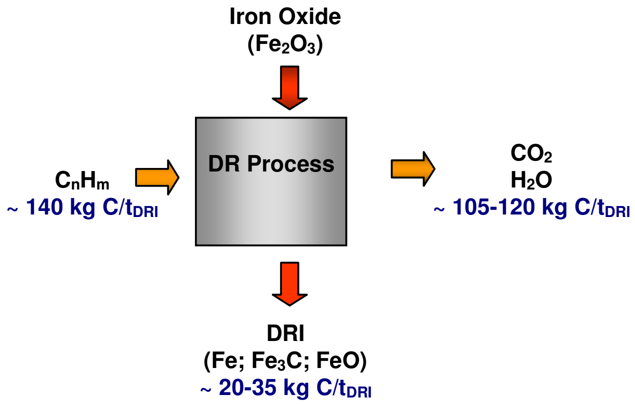

Figure 3: Carbon Balance in a DR Plant for the case of NG as source of reducing gases

A more detailed carbon balance for other DR technology is presented in Figure 4.

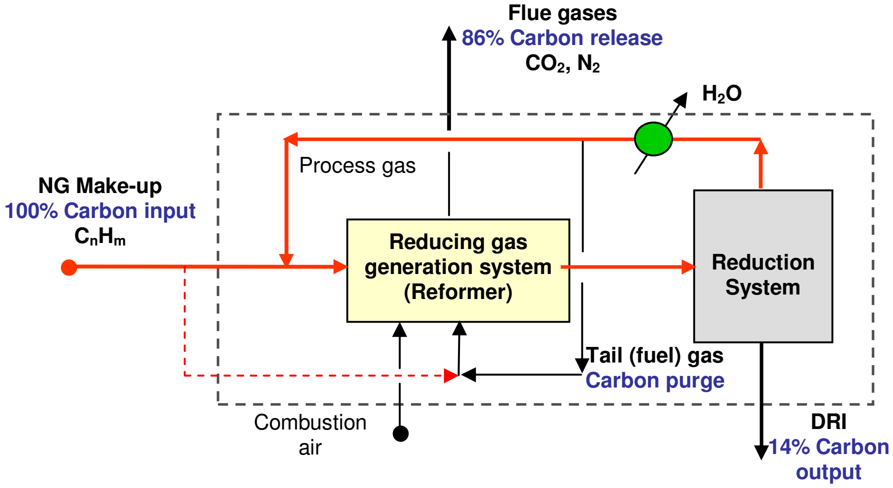

Figure 4: Carbon Balance of other DR technology

As it can be observed, for other DR technology, most of the NG make-up is used for process; with only a minor portion being diverted to balance any possible fuel need in the reformer. When an external catalytic reformer, integrated to a DR shaft, is used as the reducing gas make up source, non-selective emissions of CO_2 will issue from the reformer stack. Regardless of the internal process configuration, the Carbon input shall be equal to the output, which for this scheme is basically through the flue gases.

The corresponding balance for the ENERGIRON scheme is shown in Figure 5. What makes a unique difference between the ENERGIRON DR process and other technologies is the incorporation of a CO_2 removal system as integral part of the reduction circuit. In fact, one of the inherent characteristics of this process scheme and of high importance for this application is the selective elimination of both by-products generated from the reduction process; water (H_2O) and carbon dioxide (CO_2), which are eliminated through top gas scrubbing and CO_2 removal systems, respectively.

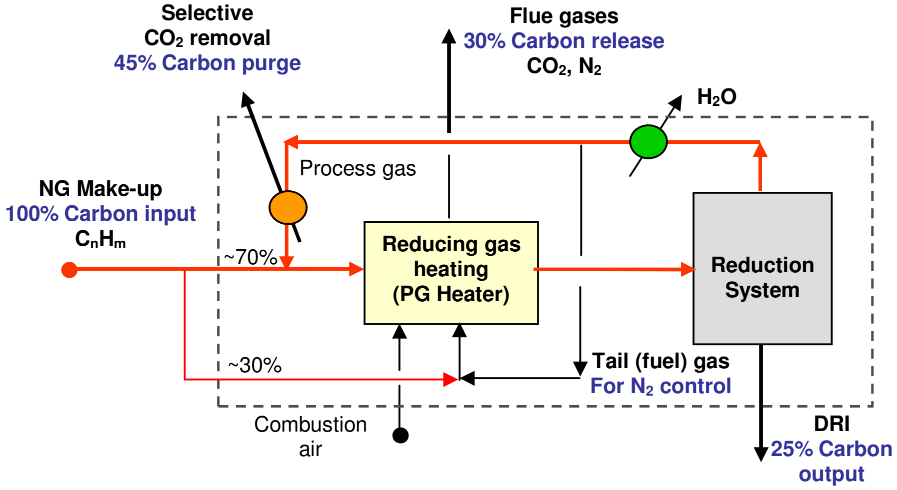

Figure 5: Carbon Balance of ENERGIRON DR process

The selective elimination of both oxidants makes possible the recycling of reducing gases (H_2 and CO) back to the DR shaft and consequently, the optimization of NG make-up as process (about 70-75% of total energy requirements). It can be observed that only 30% of total Carbon input is released as flue gases from the PG heater stack. The balance is selectively removed as pure CO_2 through the CO_2 removal system, based on chemical absorption (amines, hot carbonates solutions). Additionally, due to the high-Carbon DRI (3.5% in DRI), a significant amount of Carbon leaves the system as DRI product in the form of Fe_3C.

As rule of thumb, for the ENERGIRON DR plant using NG, about 70 kg C (or 250 kg of CO_2) is selectively removed per each tonne of DRI.

In summary, when comparing not only the BF-BOF with DR-EAF routes but also the available DR schemes available in the market, when using NG, the nature of CO_2 emissions are different. In general, for the specific location of 0.74 kg CO_2/kWh, from pellets production up to liquid steel product, total CO_2 emissions from the ENERGIRON process is about 60% of that of the BF-BOF route and 10% lower as compared to other DR technology available.

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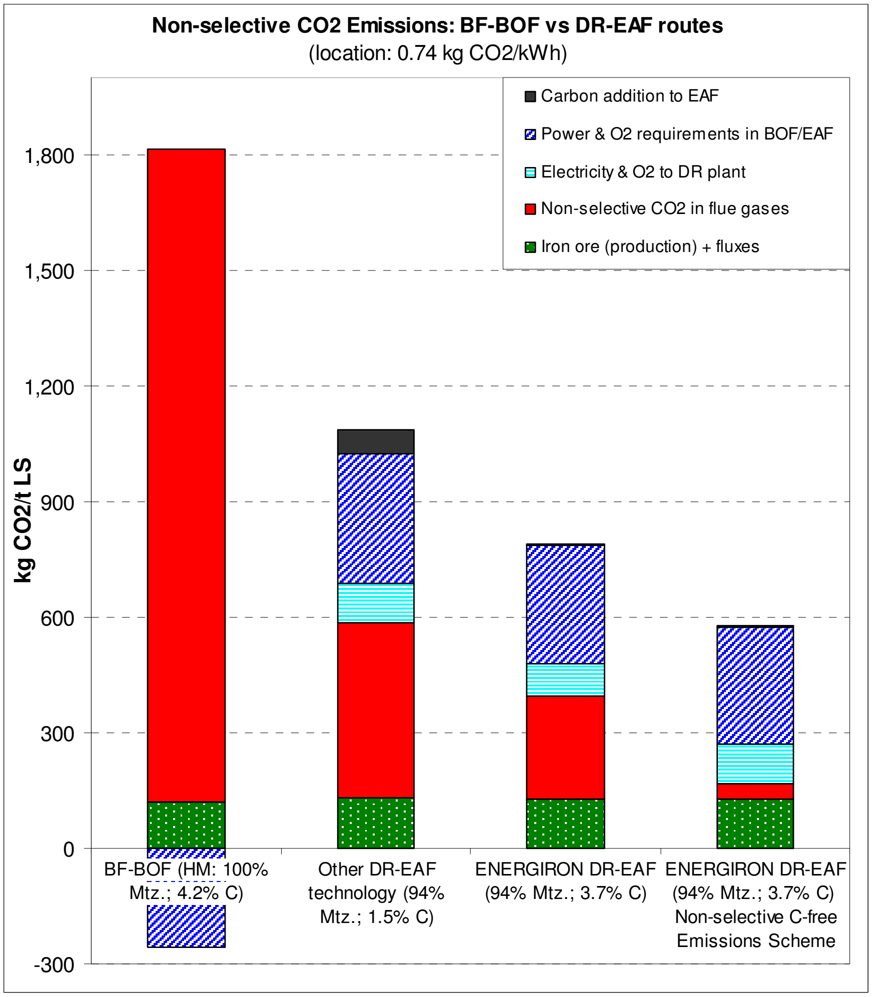

Figure 6: Non-selective CO_2 emissions (through flue gases) of ENERGIRON technology as compared to BF-BOF and other DR-EAF technologies

However, in terms of non-selective CO_2, the ENERGIRON scheme, as compared to BF-BOF scenario, emits only 50% of CO_2 through the flue gases and 30% less than other DR technologies as shown in Figure 6. The Non-selective Carbon-free Emissions Scheme, which will be discussed below, is also included in this graph. It can be observed the significant decrease of non-selective CO_2 emissions from the overall steelmaking facility with the novel ENERGIRON approach.

THE ENERGIRON DR PROCESS

The ENERGIRON Process (Figure 7), based on the ZR scheme, is a major step in reducing the size and improving the efficiency of direct reduction plants. Reducing gases are generated by in-situ in the reduction reactor, feeding natural gas as make-up to the reducing gas circuit and injecting oxygen at the inlet of the reactor. As mentioned above, 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 though chemical absorption is highly efficient and low energy consuming due to the high operation pressure of the plant.

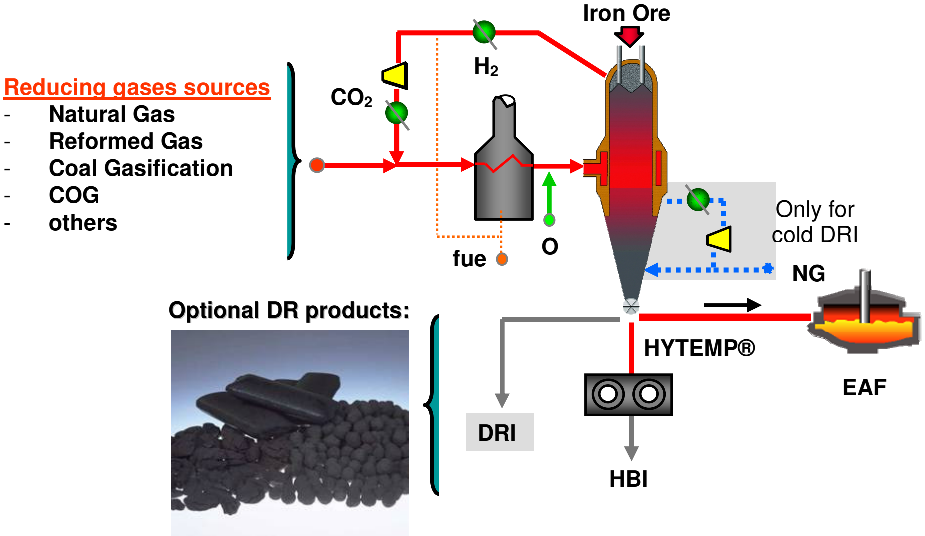

Figure 7. ENERGIRON Process Diagram

Since all reducing gases are generated in the reduction section by taking advantage of the catalytic effect of the metallic iron inside the shaft furnace, optimum reduction efficiency is attained. This means that an external reducing gas reformer is not required. Compared to a conventional DR plant including reformer, this scheme permits lower operating/maintenance costs and higher DRI quality, and the total investment for a ZR plant is also lower.

The basic ENERGIRON scheme permits the direct utilization of natural gas. With the same scheme configuration, ENERGIRON plants can also use the conventional steam-natural gas reforming equipment, which has long characterized the process. Other reducing agents such as hydrogen, gases from gasification of coal, petcoke and similar fossil fuels and coke-oven gas, among others, are also potential sources of reducing gas depending on the particular situation and availability.

Additionally, the DR plant can be designed to produce High-carbon DRI, hot DRI, which can be directly fed to adjacent EAF through the HYTEMP System or to briquetting units to produced HBI or any combination of these products.

The overall energy efficiency of the ZR process is optimized by the integration of high reduction temperature (above 1050℃), “in-situ” reforming inside the shaft furnace, as well as by a lower utilization of thermal equipment in the plant. Therefore, the product takes most of the energy supplied to the process, with minimum energy losses to the environment

The shaft furnace operates at elevated pressure (6-8 bars, absolute), allowing a high productivity of about 10 tonnes (t)/h x m² and minimizing dust losses through top gas carry-over. This is reflected in low iron ore consumption, which allows keeping the operating cost low.

A significant advantage of this process scheme that directly benefits steel makers is the wider flexibility for DRI carburization. The process allows attaining carbon levels up to 5.5%, due to the improved carburizing potential of the gases inside the reactor, which allow for the production primarily of iron carbide.

For the production of high quality DRI, i.e. 94% metallization, 3.5% carbon and discharged at 700℃, the thermal energy consumption is only 2.30 Gcal/t DRI as natural gas and just 60 to 80 kWh/ton DRI as electricity, with a remarkable low iron ore consumption of 1.35 to 1.40 t/t DRI, mainly due to high operating pressure. In this regard, it is important to note that the extremely low energy consumption, which includes CO_2 absorption and the high quality DRI in terms of metallization and high-C (higher DRI energy content), is achieved by a totally integrated and optimized energy balance. The PG Heater is designed for high temperature (above 950℃), the required reducing gas temperature is tuned with oxygen injection and the waste heat from the top gas is used for LP steam generation, which fulfills the needs of the CO_2 stripper of the CO_2 removal system. Thus, no additional energy is required for CO_2 stripping.

This makes the ENERGIRON plant, based on the ZR scheme, the most efficient direct reduction method in the field. The impact of eliminating the external gas reformer on plant size is significant. For example, a plant of 1.6-million t/year capacity requires only 60% of the area needed by other process plants for the same capacity. This can be noticed when making a benchmarking comparison as presented in Table II.

Energy Efficiency of DR Processes				
		Other DR Technology (1)	ENERGIRON ZR Technology	ENERGIRON ZR Technology (Non-selective Carbon-free Emissions Scheme)
Product Quality	Metallization	93%	94%	94%
	Carbon	2.0%	3.5%	3.5%
Energy Consumption	Nat. Gas (Gcal/t)	2.30	2.30	2.32
	Electricity + Oxygen injection (kWh/t)	100	65	100
CO_2 selective removal	Included	No	Yes (60% of CO_2 emissions)	Yes (90% of CO_2 emissions)
	as energy savings (Gcal/t)	0	-0.20	-0.28

(1) based on published data available

Table II: Comparative DR processes in terms of Total Energy Consumption related to DRI quality and Selective CO_2 removal

This plant configuration has been successfully operated since 1998 with the HYL DR 4M plant and was also incorporated (in 2001) in the 3M5 plant, both at Ternium in Monterrey. With the same ZR scheme, one more is in operation in Abu Dhabi and the largest ever DR plant of 2.0 million t/y is under construction in Egypt.

FURTHER STEP FOR SELECTIVE CO_2 REMOVAL IN THE ENERGIRON DR PROCESS

As a natural development in the ENERGIRON DR technology, a maximum selective removal of CO_2 can be achieved in a simple and efficient way and taking advantage of the features of the process scheme.

In the ENERGIRON direct reduction plant, the main emission sources of CO_2 are located (1) in the absorber column of the CO_2 removal plant (characterized as a selective CO_2 emission) and (2) in the process gas heater stack (characterized as a non-selective CO_2 emission). In addition, when an external catalytic reformer is used as the reducing make up gas source, an additional non-selective emission of CO_2 will issue from the reformer stack.

As a consequence of the increasing concern about the greenhouse effect attributed to the increased presence of CO_2 in the atmosphere, measures have to be considered to limit the consequences of this problem in the world. A first measure is essentially to reduce the CO_2 emissions to the atmosphere. For this reason, DRI producers are facing the necessity to develop direct reduction processes where the CO_2 emissions to the atmosphere are significantly decreased.

The new development provides a unique method for the ENERGIRON direct reduction plant, which comprises the basic chemical absorption system to extract a stream of almost pure CO_2 from the spent gas removed from the reactor, the heater, (and an external reformer, when applicable) resulting in use mainly of H_2 as the fuel for the burners; in this way essentially a carbon free emission is released from the heater (and/or reformer) stack.

The concept is very simple; to separate the carbonaceous compounds from the recycling gas (after CO_2 absorption), feeding them back to the reduction circuit and using the separated H_2 as fuel instead of tail and/or natural gas.

This approach provides the H_2 required as fuel from the reduction system itself. As shown in Figure 8, the only addition to the basic ENERGIRON scheme is the incorporation of a physical adsorption system (PSA type), which is used to recover hydrogen from a portion of the gas stream previously upgraded by the chemical CO_2 absorption plant. Hydrogen separation may also be carried out by other means, for example gas separation membranes, including a combination of PSA/VPSA and gas membranes, which automatically diverts to the chemical absorption unit the carbonaceous compounds where almost all the CO2 is withdrawn from the system as pure technical gas.

The only carbon-containing fuel burned in the heater (and/or the reformer), which involves the release of CO_2 after combustion reactions, is a small amount of reducing gas; comprising CO, CO_2 and CH_4, necessarily removed from the system to purge inert elements (like nitrogen) which otherwise accumulate continuously, and, if needed, a minimum stream of natural gas required to produce a visible flame that allow safe monitoring of burner ignition.

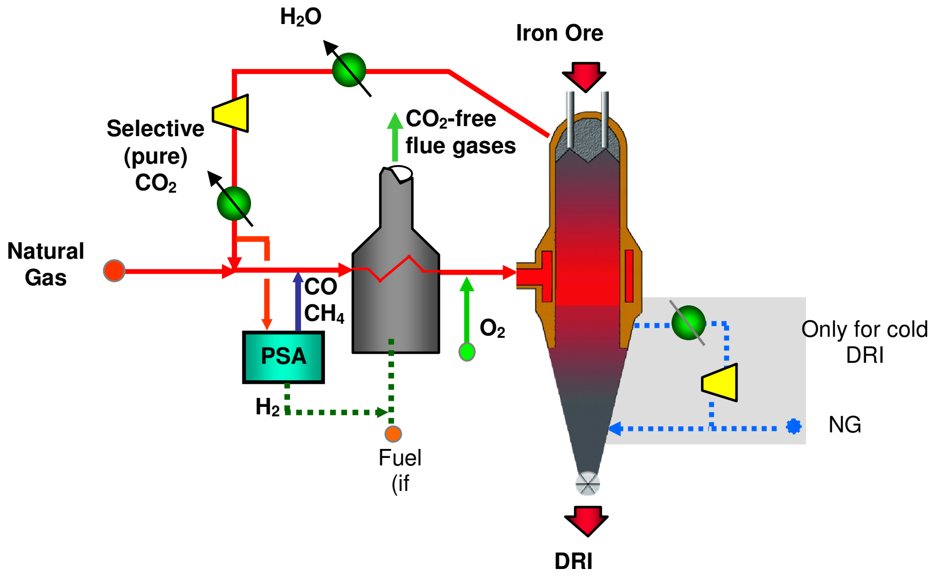

Figure 8. ENERGIRON Process Diagram for CO_2-free non-selective emissions (~ 90% selective CO_2 removal)

In this way, the heater burners (and reformer burners, when applicable), are mainly fed with hydrogen instead of carbon bearing fuels.

This highly efficient and simple approach is based on the fact that the ENERGIRON DR plant (1) has a selective CO_2 absorption system as part of the reduction circuit and (2) operates at 8 bars; therefore, the only need is a PSA, which takes advantage of the available pressure to separate the H_2 without any additional energy required for this task and thus preventing any other direct and/or indirect non-selective CO_2 emissions, which may eventually be associated with additional thermal and/or electric power requirements. There is the need of a compressor to recycle the purge gas from the PSA back to the circuit, which implies additional marginal power consumption.

With this scheme, ENERGIRON plants can provide a completely green approach, since about 90% of total carbon input will be available as pure CO_2 for further use. Flue gases consist basically of water vapor (and N_2 from the combustion air).

This approach can be easily incorporated to existing HYL/ENERGIRON plants with minimum capital cost.

ACTUAL SITUATION OF CO_2 USE IN HYL/ENERGIRON DR PLANTS

Since 1998, CO_2 gas, from the CO_2 absorption system of HYL/ENERGIRON plants, has been used as byproduct by different off-takers. It is important to note that, depending on: (i) iron ore composition, (ii) natural gas analysis, (iii) absorbing solution used in the CO_2 absorption system, the CO_2 stream from the DR plant may contain some sulphur –in the range of ppm- (in case of amines-based solution) or to be without any contaminant (as the case of hot carbonates-based solutions).

The current scenario of CO_2 from HYL/ENERGIRON DR plants is as follows:

- Ternium DRI plant at Monterrey, Mexico, sells the raw CO_2 output to Praxair, which after further cleaning, distributes the gas for food and beverages industries.

- Ternium DRI plant at Puebla, Mexico, which clean CO_2 is being sold to Infra for further use in beverages.
- PTKS DRI plant in Indonesia, provides the CO_2 to Janator, for final use in the food industry.
- PSSB DRI plant in Malaysia, sells the CO_2 to Air Liquid/MOQ for further cleaning and application in the food industry.
- Welspun Maxsteel Ltd. HBI/DRI plant of India is providing pure CO_2 to Air Liquid for production of dry ice.
- The two new ENERGIRON direct reduction plants at Emirates Steel in Abu Dhabi, each of 1.6 million t/y of DRI, will allow Emirates Steel to commercialize the CO_2 as a byproduct. About 25% of total CO_2 will be compressed and then pumped into oil wells instead of natural gas to boost oil production. The company expects the venture will become the world's largest CO_2 capture and EOR project.

There are also some other potential CO_2 commercialization projects for the HYL DR plant of ArcelorMittal at Lázaro Cardenas, Mexico.

The above facts indicate the current trend in steelmaking for decreasing CO_2 emissions, by using the CO_2 from DR plants as byproduct for diverse applications, the sources of which would otherwise come from other fossil fuel combustion systems. We should not neglect to mention that what for many is an environmental problem, for this type of plant it is a lucrative source of added income.

REMARKS

The ENERGIRON DR process intrinsically includes a CO_2 absorption system for the selective elimination of CO_2, leaving only 30% of total Carbon entering the process as non-selective emission through flue gases from the PG heater stack. CO_2 stripping is achieved by using the top gas waste sensible heat, avoiding the need of additional energy requirements.

For this specific and important issue and for steelmakers conscious of their role in redefining steelmaking with a key aspect of decreasing CO_2 greenhouse gas emissions, ENERGIRON technology offers the unique option available in the market for production of DRI while obtaining pure CO_2 as a natural byproduct of the process. This is done without the need of additional thermal or electrical energy, which eventually will imply further direct and/or indirect non-selective CO_2 emissions. With this proposed efficient and simple approach, a complete non-selective CO_2-free emissions "green" DR plant is now available in the market.

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