By-products and emissions in the ENERGIRON direct reduction process

Steel production via the DRI-EAF route produces significantly less CO_2 than the integrated BF-BOF route with its dependence on coal as the primary reductant. The latest ENERGIRON ZR direct reduction plants produce even less than other DR processes and, following desulphurisation, the waste gases provide a valuable CO_2 resource for other industries such as food and oil exploration.

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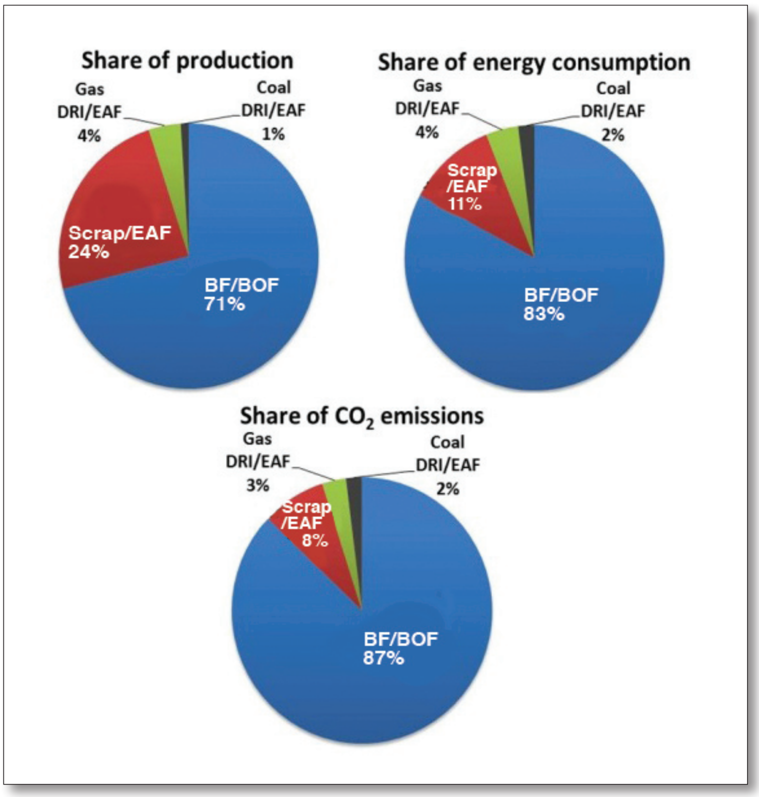


Fig 1 Steel production, energy consumption and CO_2 emissions share by steelmaking route [1]

The steel industry is characterised by intensive use of fossil fuels, with a significant impact on the environment through global warming by 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 direct reduction DR-EAF route the reductants can be either natural gas (NG), or syngas and coke oven gas (COG) produced by coal gasification.

Based on the use of coal in the BF-BOF route and NG in the case of the DR-EAF route, the DR-EAF route emits 40-60% less CO_2 (depending on local conditions).

Besides GHG emissions, there are a number of by-products and pollutants that can have severe environmental impact and which require special attention, specifically for the BF-BOF route. In 2012, the integrated BF-BOF route represented about 71% of world steel production, but 82% of energy consumption and 88% of CO_2 emissions (see *Figure 1*). The other process routes are similarly illustrated in the figure.

Figure 2 shows the broad regional distribution of production, energy and emissions. About 48% of steelmaking in Europe is EAF-based, while in NAFTA it is ~59%. Asian plants (OECD) represent only 29% via EAF. The Asian integrated plants are, however, generally modern.

BRIEF DESCRIPTION OF THE ENERGIRON DR PROCESS

Tenova HYL is a pioneer in the direct reduction industry; the first facility being built in 1957 in Monterrey, Mexico. Developments have occurred over the years and, in 1998, the innovative ZR technology was industrially implemented offering a more efficient DR process producing unique high carbon DRI, hot DRI charging with the Hytemp system and the lowest environmental impact of the DR technologies. This technology is now being commercialised under the Energiron strategic alliance as ENERGIRON ZR.

This process, which has no external gas reformer, provides unmatched flexibility for any reducing gas source in any region, and uses the widest range of iron ore feedstocks and qualities.

The ENERGIRON ZR process (see *Figure 3*) is a major step 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, something that has long characterised the process. Other reducing agents, such as hydrogen, syngas produced from coal gasification systems, 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 case, 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. The ENERGIRON 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.

Operating conditions of the ZR process are characterised by high temperature (>1,080°C) and high pressure (6-8 bar A at top gas exit). The elevated pressure allows a high productivity of about 10t/h x m (high pressure means lower gas velocities so less area is required for a certain gas flow) and low reducing gas velocities of about 2m/sec, as compared to lower operating pressure processes for which the gas velocities are >5m/sec. This minimises dust losses through top gas carry-over and so lowers the overall iron ore consumption, which in turn lowers the overall operating costs.

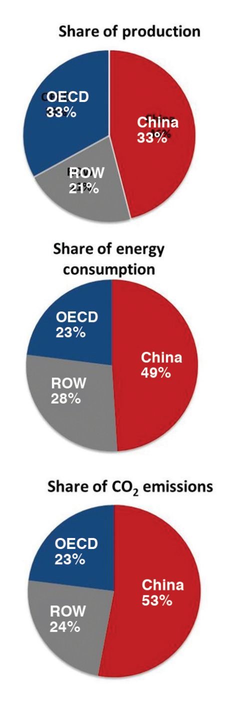
A distinct advantage of this process without an integrated reformer is the wider flexibility for DRI carburisation. DRI carbon levels up to 5% can be obtained due to the high methane (CH_4) concentration within the H_2-CO and the high temperature of the bed(>860°C), which favours the diffusion of carbon into the iron matrix and the precipitation of iron carbide (Fe_3C). A modern unit is shown in *Figure 4*.

CO_2 EMISSIONS IN BF-BOF VS. DR-EAF

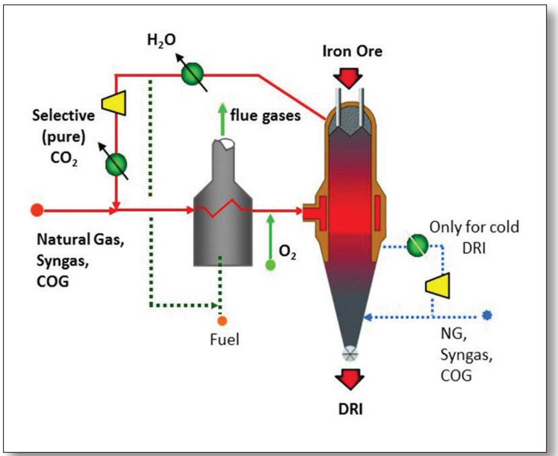
The scenario is based on the comparison between the DR/EAF and the BF/BOF routes for manufacturing of hot roll coils, via a ladle furnace and thin slab caster or compact strip plant (CSP) as illustrated in *Figures 5a* and *5b* which also show the schematic energy distributions in the two routes. Note the EAF charge is 100% DRI.

The major gaseous fuel by-products, which are recovered are blast furnace gas (BFG), COG and BOF gas. Energy balances show that most of the gas energy is used for power generation or even flared. Since 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 imported.

It should be noted that the optimised utilisation of primary fossil energy also has the effect of significantly reducing the specific CO_2 emissions per tonne of steel. For ▷



▶ Fig 2 **World steel production, energy share consumption and CO_2 emissions by region [1]**



▲ Fig 3 **ENERGIRON ZR process schematic**

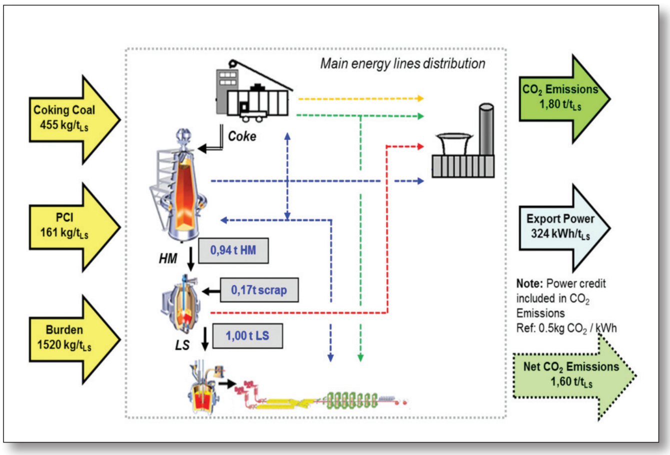


Fig 5a **Energy distribution in integrated steelworks**

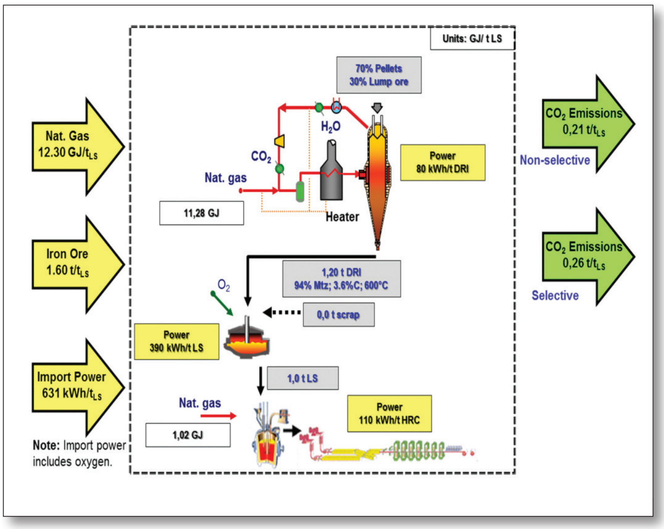


Fig 5b **Energy distribution in DR-EAF mill route**

Fig 4 **Suez Steel ENERGYIRON plant, Egypt**

this optimised scheme, the specific CO_2 emission in flue gases via the conventional BF/BOF route is about 1.8t CO_2/t of liquid steel. The DR/EAF route is represented in *Figure 5b* by an ENERGIRON ZR-based DR plant for high-C DRI production as 100% feed to the EAF.

The main observations are related to the fact that while the integrated steel plant is a net exporter of electricity, the DR-EAF route is a net importer. By using the ZR route, more than half of the gaseous CO_2 is selectively removed; this provides 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 0.3kg CO_2/kWh and others like India where it is 0.9kg CO_2/kWh.

A steel plant based on DR-EAF using natural gas for DRI production is unlikely to be located in countries where coal is the main energy source, just as an integrated steel plant is unlikely to be located in countries with significant natural gas resources. However, there are countries which do use both energy sources for steel production.

The difference between BF-BOF and DR-EAF as shown in *Figures 5a* and *b* in terms of CO_2 emissions is clearly evident. (In *Figure 5b* non-selective is the CO_2 from combustion in the furnace mixed with N_2 from the air. Selective is the CO_2 removed via a chemical absorption or a physical adsorption system in our process).

CO_2 EMISSIONS IN AN ENERGIRON DR PLANT

GHG emissions may be significantly different between the two leading technologies for production of DRI. Regardless of whether using natural gas (CH_4), syngas or COG, the make-up of reducing gases to a DR plant contains carbon, either in the form of hydrocarbons and/or carbonaceous compounds (CO, CO_2). Also, regardless of the DR process configuration, only 15-40% (depending on the carbon content in the DRI) exits the process as combined carbon in the DRI, the remainder being as CO_2.

Because the DRI from the ENERGIRON ZR process contains more carbon, less carbon is removed in the form of CO_2. This higher carbon content in DRI has been well documented in various papers, being shown to be beneficial in the steelmaking process by providing chemical energy to the furnace and for making it more efficient.

The difference can be seen when a DR configuration with an external catalytic reformer integrated to a DR shaft is used as the reducing gas make-up source. From total process natural gas makeup, containing 140kgC/t DRI, about 25kgC/t DRI (17%) exits as part of the DRI and the balance is released as flue gas from the reformer (see *Figure 6*). These figures compare with 110kg/t DRI, from which 40kg C/t DRI (36%) is in the DRI produced via the ENERGIRON ZR process as shown in *Figure 7*.

In addition, of the remaining 70kg C/t DRI, 65kg are selectively removed as pure CO_2, which can be used for other applications or sequestrated. The elimination of both by-products generated from the reduction process water (H_2O) and carbon dioxide (CO_2) – improves the gas utilisation in the process to more than 95%.

In summary, the ENERGIRON configuration provides inherent selective elimination of about 65% of total carbon input as CO_2 (about 240kg CO_2/t DRI), which when commercialised, significantly reduces CO_2 emissions – a clear advantage of the technology.

OVERALL ANALYSIS OF CO_2 EMISSIONS

Figure 8 compares CO_2 emissions for the BF-BOF route, ENERGIRON ZR with and without CO_2 commercialisation and/or sequestration, and a competing DR technology. The analysis refers to a location producing 0.54kg CO_2kWh (typical of that prevailing in some states in USA). Electricity generation is a composite of sourcing from natural gas, coal, hydraulic, eolic, nuclear, biomass and, depending on the particular location – the values of kg CO_2/kWh shown, are an average of the COv emitted from this sources, in the mentioned countries.

In summary, the DR-EAF route is characterised by having about 50% of the CO_2 emissions of the BF-BOF route, with ENERGIRON ZR 10-45% lower than the competing DR technology.

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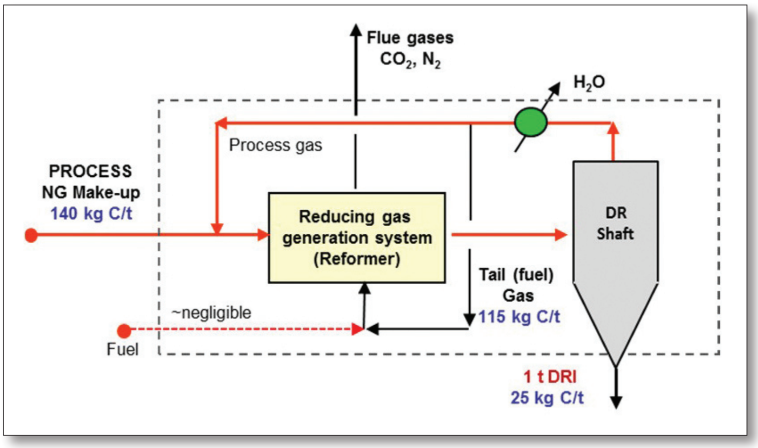

Fig 6 **Carbon balance for a DR plant with integrated reformer**

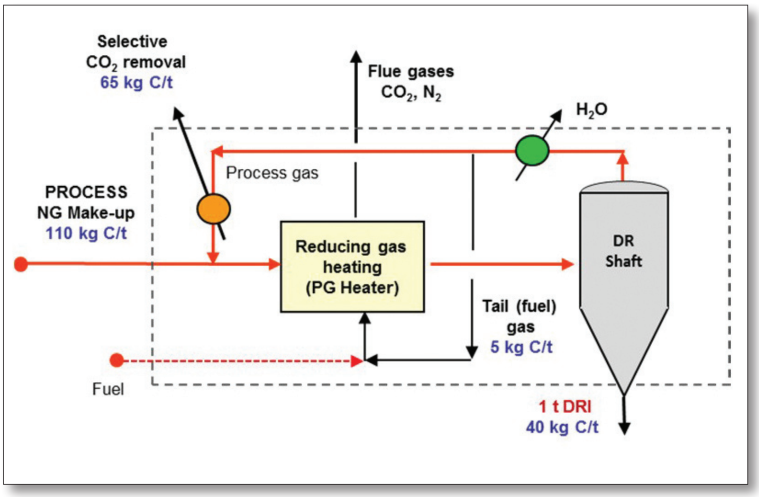

Fig 7 **Carbon balance for a DR plant based on the ENERGIRON ZR process**

COMMERCIALISATION OF CO$_2$ PRODUCTION

Since 1998, CO$_2$ gas from the CO$_2$ absorption system of HYL/ENERGIRON plants has been used as a CO$_2$ source by other users – turning a hitherto environmental problem into a source of added income. It is important to note that this is dependent on the iron ore composition, natural gas analysis and the absorbing solution used in the CO$_2$ absorption system. In the case of amine-absorbing solutions, both CO$_2$ and H$_2$S are removed and thus the CO$_2$ stream from the DR plant may contain some H$_2$S (~200 ppm). To remove the H$_2$S, there are a number of possibilities: passing the CO$_2$ stream through an incinerator for conversion of H$_2$S to SO$_2$, or passing the CO$_2$ stream through a sulphur removal system, like Sulferox®.

The current situation regarding CO$_2$ utilisation from HYL/ENERGIRON DR plants is as follows:

- **Ternium DRI plants at Monterrey, Mexico** The raw CO$_2$ output from the plants of 0.7Mt/yr cold DRI and 1.0M t/yr hot DRI have, since the late 1990s, been sold to Praxair who, after further cleaning, distributes the gas for the food and beverage industries.
- **Ternium DRI plant at Puebla, Mexico** Clean CO$_2$ is being sold to Infra for further use in beverages from a DR module of 0.7M t/yr cold DRI.
- **PTKS DRI plant in Indonesia** Two modules of 0.75Mt/yr cold DRI each (in idle conditions since 2013 due to lack of NG) provided the CO$_2$ to Janator for final use in the food industry.
- **PSSB DRI plant in Malaysia** Two modules of 0.60Mt/yr cold DRI each (in idle conditions since 2012 due to lack of NG), used to sell the CO$_2$ to Air Liquid/MOQ for further cleaning and application in the food industry.
- **JSW-Salav in India** A module of 0.75Mt/yr DRI HBI/DRI is used to provide CO$_2$ to Air Liquid for production of dry ice.
- **Emirates Steel in Abu Dhabi** For the two ENERGIRON plants, each of 2.0Mt/y of hot DRI plus the Micromodule of 0.2Mt/yr cold DRI, there is a project for a CO$_2$ capture facility as part of the collaboration between Masdar, ADNOC and Emirates Steel to explore feasibility to reduce the carbon footprint of the Emirate and make CO$_2$ available for enhanced oil recovery operations.
- **Nucor Steel Louisiana in USA** The largest DR ZR module ever built in the world of 2.5Mt/yr DRI (see *Figure 9*), includes a Sulferox® system for desulphurisation of the CO$_2$ stream, yielding pure CO$_2$, which will be commercialised as a valuable by-product.

WASTES AND BY-PRODUCTS

Iron ore-based steelmaking accounts for about 75% of

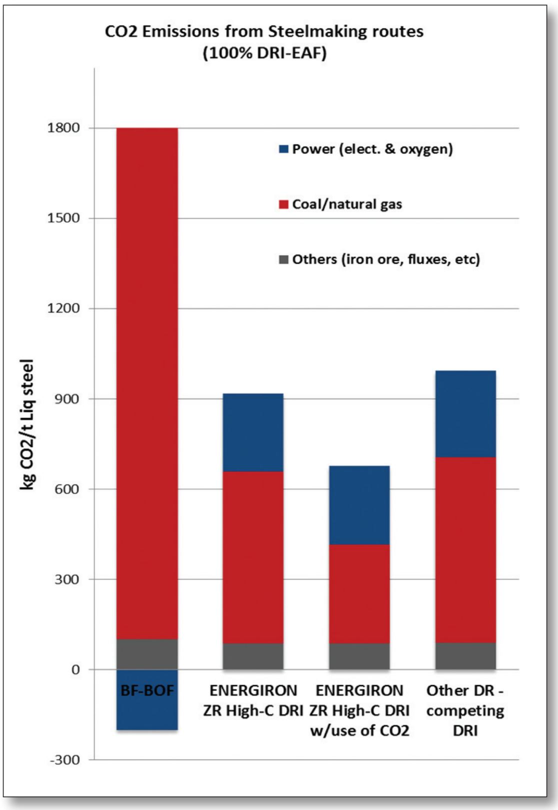

Fig 8 CO$_2$ emissions from BF-BOF and alternative DR routes

Fig 9 Nucor Steel Louisiana DR plant with CO$_2$ absorption and sulphur removal system

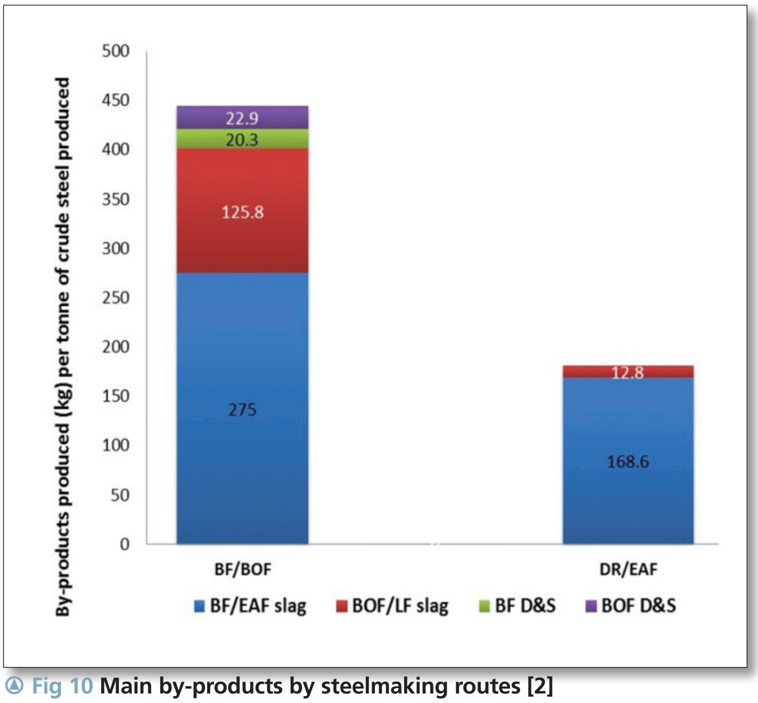

Fig 10 Main by-products by steelmaking routes [2]

	BF/ BOF	EAF	ENERGIRON DRI
Energy consumption (GJ/t)	22	5.8	10
CO_2 equivalent emissions (tCO_2eq/t)	2.1	0.7	0.4
Water consumption (m^3/t)	2.6	0.6	0.8
Land use (m^2/t)	1.7	0.5	0.4
Emissions to air (kg/t)			
NO^X	1	0.04	0.2
SO_2	1	$7.4*10^{-4}$	
CO	56	9.8	
PM_{10}	0.15	0.14	0.13
$PM_{2.5}$	$1.4*10^{-2}$	$0.3*10^{-2}$	$7.7*10^{-2}$
Pb	$2.6*10^{-4}$	$1.4*10^{-4}$	
Hg	$9.8*10^{-6}$	$0.1*10^{-6}$	
As	$6.2*10^{-6}$	$6.6*10^{-6}$	
Cr^{6+}	$4.5*10^{-6}$		
Ni	$3.5*10^{-5}$	$1.6*10^{-5}$	
Cd	$8.1*10^{-6}$	$0.5*10^{-6}$	

Table 1 Main emissions by steelmaking routes [3]

world steel production. The main inputs are iron ore, coal, and limestone and the main by-products are slag (about 90%), sludge and dusts.

On average (see *Figure 10*) the amount of these by-products exceeds 400kg/t crude steel, whereas for the DR-EAF route it is less than 200kg/t crude steel. Slag is made up of mixtures of silicon, calcium, magnesium, aluminum and iron oxides, as by-products coming from refining and fluxes used during the steelmaking process.

In addition, there are effluents from the BF-BOF route which are related to the use of coal as the primary energy source: BTX (light oil vapour), tar vapours, naphthalene vapour, ammonia gas, hydrogen sulphide gas and hydrogen cyanide gas; all of which require specific and special treatment. COG is normally used as fuel at the coking battery and steel works, and flushing liquor is recirculated to the coke oven plant, waste water is discharged to treatment plant; ammonia/ammonia sulfate is sold as by-product and light oil (if recovered) is also sold as by-product and sulphur/sulphuric acid (if gas is desulphurised), is sold as a by-product. All these make the emissions treatment very intensive and expensive, which is ultimately reflected in higher CAPEX and OPEX requirements.

Table 1 summarises energy and emmissions for the various routes. NO_x and SO_2 emissions are an order of magnitude higher for the BF-BOF route. Other metals are also higher for this route. (Note: no credit due to electricity co-generation from the integrated route is reflected in the CO_2 emissions).

CONCLUSIONS

The ENERGIRON process is the most feasible DR technology, already designed and prepared for maximum CO_2 emissions reduction in steelmaking while processing virgin metallic units. Due to its inherent characteristics, it complies with the strictest environmental regulations worldwide, while disposing of some effluents and emissions as valuable by-products. **MS**

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