Blast Furnace CO_2 Emissions Techno-Economic Assessment

R. van Laar, H. Sultan, D. Verma, J. de Weerdt, Danieli Corus BV, The Netherlands

Decarbonization is a key strategic objective for the steelmaking industry. BF-BOF steelmaking is anticipated to remain dominant coming decade due to its efficiency, economic benefits, and constraints associated with alternative technologies. Therefore, it is essential to focus on reducing CO_2 emissions from blast furnaces. This paper provides a detailed techno-economic assessment of the most effective and immediate strategies to achieve significant reductions in BF CO_2 emissions.

KEYWORDS: BLAST FURNACE, CO_2 EMISSIONS, TECHNO-ECONOMIC ASSESSMENT

INTRODUCTION

Our steelmaking industry is challenged by decarbonization requirements and several companies are already converting BF-BOF to (DRP-)EAF steelmaking to reduce the CO_2 emissions. We are assuming, however, that many BF-BOF's will be retained coming decades at large capacity due to several intrinsic advantages and economics. This motivates us to contribute to decarbonization of BF-BOF steelmaking and advance effective technologies. This also allows immediate implementation as we are considering technologies which could be deployed right now.

The emissions generated within BF ironmaking are currently the largest contributor within a typical integrated BF-BOF steelmaking plant and its emissions reduction is therefore critical. It is important to determine the most effective and economic methods to reduce these emissions.

This paper will first summarize the set-up of our integrated CO_2 model and the results for two methods to reduce the emissions i.e., 1) injection of gas in the BF and 2) usage of gas to produce DRI and charge this DRI in the BF.

The paper will then explain the set-up of the economic calculations for a typical EU steelmaking plant whereas DRI could be produced on-site (using COG, NG or H_2) or in GCC (using NG or H_2).

TECHNICAL ASSESSMENT CO_2 EMISSIONS

We have compiled a model to compare Scope 1 and Scope 2 CO_2 emissions of a typical integrated BF-BOF steelmaking plant. This model includes sintermaking, pelletmaking, cokemaking, ironmaking (BF and DRP), steelmaking & casting and also electricity, hydrogen, oxygen & steam. Specific data are listed in Table 1.

Tab. 1 - Specific Emissions and Electricity Data

Sintermaking	$kgCO_2/tSinter$	262
Pelletmaking	$kgCO_2/tPellets$	137
Cokemaking	$kgCO_2/tCoke$	224
Steelmaking BOF	$kgCO_2/tLS$	151
Casting	$kgCO_2/tCS$	100
Electricity Grid Carbon Intensity	gCO_2/kWh	0 - 500
Sintermaking	kWh/tSinter	50
Pelletmaking	kWh/tPellets	50
Cokemaking	kWh/tCoke	50
Ironmaking DRP	kWh/tHBI	100
Hydrogen	kWh/kgH_2	55
Ironmaking BF	kWh/tHM	100
Steelmaking BOF	kWh/tLS	30
Casting	kWh/tCS	100
Oxygen	kWh/Nm^3	0.3

We have defined a typical modern and efficient BF according to Table 2. The burden of this BF comprises 80% sinter and 20% pellets.

Tab. 2 - Blast Furnace Data

Working Volume	m^3	3800
Hearth Diameter	m	14
Production	tHM/d	11500
Coke Rate	kg/tHM	313
Coal Injection Rate	kg/tHM	180
Top Gas Temperature	°C	109
RAFT	°C	2170

Crude Steelmaking Scope 1 emissions according to our model amount to 1983 $kgCO_2/tCS$ and the composition is illustrated in Figure 1.

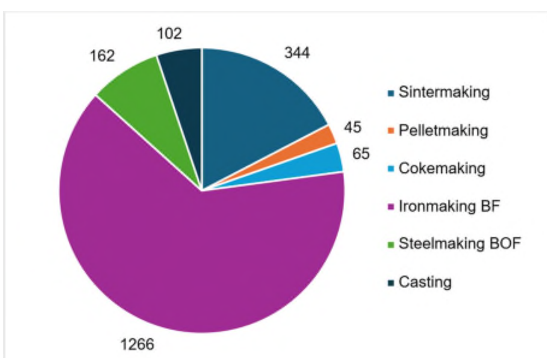

Fig. 1 - Crude Steelmaking Scope 1 CO_2 Emissions

The electricity balance of our reference plant is negative: this plant exports electricity produced by COG, BFG and BOFG.

We have compared the effect of two decarbonization strategies:

1. Injection of gas in the BF
2. Usage of gas to produce DRI and charge this in the BF

Scope 1 Emissions: Injection of gas in the BF

The effect of injection of gas in the BF has been evaluated considering Natural Gas, Coke Oven Gas and Hydrogen. The results of our heat and mass balance calculations are summarized in Table 3. Top gas temperature and RAFT results are within acceptable limits.

Tab. 3 - Results heat and mass balance calculations

	Unit	BF	BF + NG	BF + COG	BF + H_2
Coke Rate	kg/tHM	313	387	288	278
Coal Injection Rate	kg/tHM	180	0	180	180
Gas Injection Rate	kg/tHM	0	100	40	20
Top Gas Temperature	°C	109	129	132	95
RAFT	°C	2170	1905	2031	2028

Scope 1 emissions according to our model are illustrated in Figure 2.

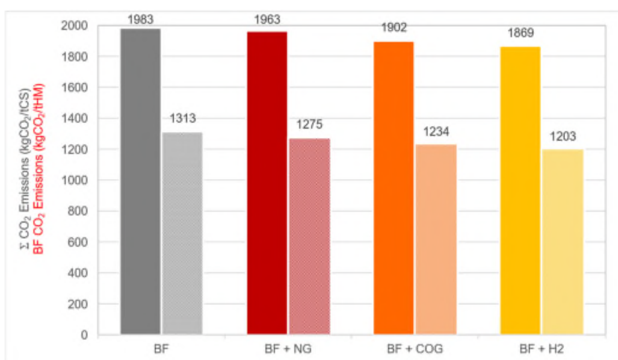

Fig. 2 - Crude Steelmaking and BF Ironmaking Scope 1 CO_2 Emissions

Injection of gas in the BF has a limited effect in reducing Scope 1 emissions. The main reasons for this relate to thermodynamics, kinetics, physics and operating limits of the BF when injecting gas.

Gas injection in the BF has a more significant effect on the integrated plant electricity balance. These effects are different for either injection of Natural Gas, Coke Oven Gas or Hydrogen.

The calorific value of the BF top gas increases when injecting gas in the BF, but the flow rate may either increase (Natural Gas) or decrease (Hydrogen) or remain approximately the same (Coke Oven Gas). Injection of Coke Oven Gas, however, reduces the amount of electricity which could be produced by using Coke Oven Gas otherwise. Hydrogen injection has a significant impact on the electricity balance as we are assuming that Hydrogen will be produced by electrolysers at a typical contemporary electricity consumption rate of 55 kWh/kgH_2.

The integrated plant electricity balance for four cases is summarized in Table 4 and clearly reflects the effects of gas injection in the BF. The electricity balance is critical when accounting for Scope 2 emissions with realistic electricity grid carbon intensities assuming that green electricity will not be available at sufficient quantities for our industry in the coming decades except for some specific plants.

Tab. 4 - Electricity Balance (negative = export of electricity, positive = import of electricity)

		BF	BF + NG	BF + COG	BF + H_2
Electricity Balance	(kWh/tCS)	-124	-279	-22	824

Scope 1 Emissions: Usage of gas to produce DRI and charge this in the BF

We have also evaluated the effect of using gas for the production of DRI and charge this DRI in the BF. DRI could either be made in EU or in GCC. We have considered the same three gases for the production of on-site DRI in EU i.e., Natural Gas, Coke Oven Gas and Hydrogen. DRI made in GCC is limited to using either Natural Gas or Hydrogen.

The energy requirements for the Direct Reduction Plant differs for these three gases as indicated in Table 5. Furthermore, we have been considered three different types of Direct Reduction Plant Process Gas Heaters (PGH). These include a conventional PGH using Natural Gas, an alternative PGH using Blast Furnace Gas and an electric PGH when using Natural Gas, Coke Oven Gas and Hydrogen for the Direct Reduction Plant, respectively.

Tab. 5 - Direct Reduction Plant Energy Requirements

Parameter	Unit	NG	COG	H2
DRP Energy Requirement	(Gcal/(tDRI)	1.6	1.5	1.4

We have assumed that DRI will be made from BF Grade Pellets according to the data in Table 6.

Tab. 6 - BF Grade Pellets and DRI Compositions

	BF Grade Pellets	DRI (Fe 82%)
Fe total	62.8%	82.6%
Fe2O3	89.4%	0.0%
FeO	0.4%	6.4%
Metallization		94.0%

The results of our heat and mass balance calculations are summarized in Table 7. Top gas temperature and RAFT results are within acceptable limits. These calculations include a burden comprising 50% sinter, 20% pellets and 30% DRI.

Tab. 7 - Results heat and mass balance calculations

	Unit	BF	BF + DRI
Coke Rate	kg/tHM	313	259
Coal Injection Rate	kg/tHM	180	120
Top Gas Temperature	°C	109	142
RAFT	°C	2170	2028

Scope 1 emissions according to our model are illustrated in Figure 3.

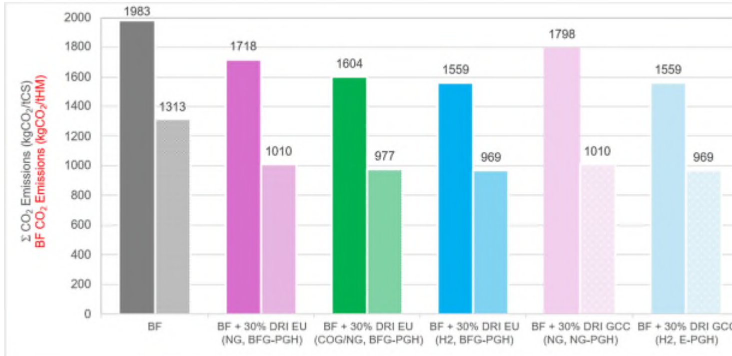

Fig. 3 - Crude Steelmaking and BF Ironmaking Scope 1 CO_2 Emissions

These data illustrate that Scope 1 CO_2 emissions could be reduced significantly when using gas to produce DRI and charge this DRI in the BF, particularly when using Coke Oven Gas or Hydrogen. CO_2 emissions are lower due to the efficient utilization of gases in the iron ore direct reduction process. When injected directly into the blast furnace, these gases are only partially consumed for reduction. In contrast, in a direct reduction plant, the gases are recycled, maximizing their use in reducing iron ore and thereby improving the overall utilization and efficiency.

Scope 2 CO_2 emissions are determined by the integrated plant electricity balance which is summarized in Table 8.

Tab. 8 - Electricity Balance (negative = export of electricity, positive = import of electricity)

		BF	BF + DRI EU (NG, BFG-PGH)	BF + DRI EU (COG/NG, BFG-PGH)	BF + DRI EU (H2, BFG-PGH)	BF + DRI GCC (NG, NG-PGH)	BF + DRI GCC (H2, E-PGH)
Electricity Balance*	(kWh/tCS)	-124	106	307	1264	-27	1532

* Including electricity requirment for DRI plant and hydrogen production.

Scope 1 and 2 Emissions

Our model also accounts for Scope 2 emissions, which are relevant unless economical green electricity would be available for our industry. It is assumed this is not realistic in the coming years for many countries currently operating integrated BF-BOF steelmaking plants. Geographical electricity grid carbon intensities of 2024 are illustrated in Figure 4 and clearly reflect the fact that these intensities currently exceed 200 – 500 gCO$_2$/kWh in many regions (exceptions include Scandinavia, Brazil and France).

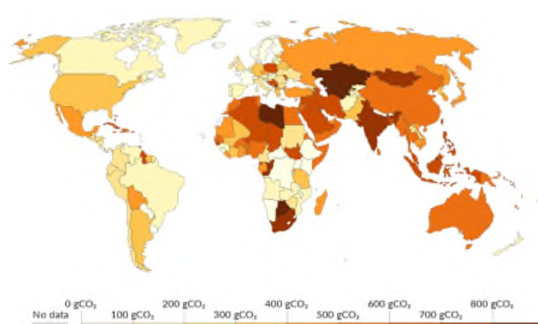

Fig. 4 - Electricity grid carbon intensity

Scope 2 emissions are directly related to the integrated plant electricity balances: higher electricity imports cause larger Scope 2 emissions. Scope 1 and Scope 2 emissions for all scenarios according to our models are illustrated in Figure 5.

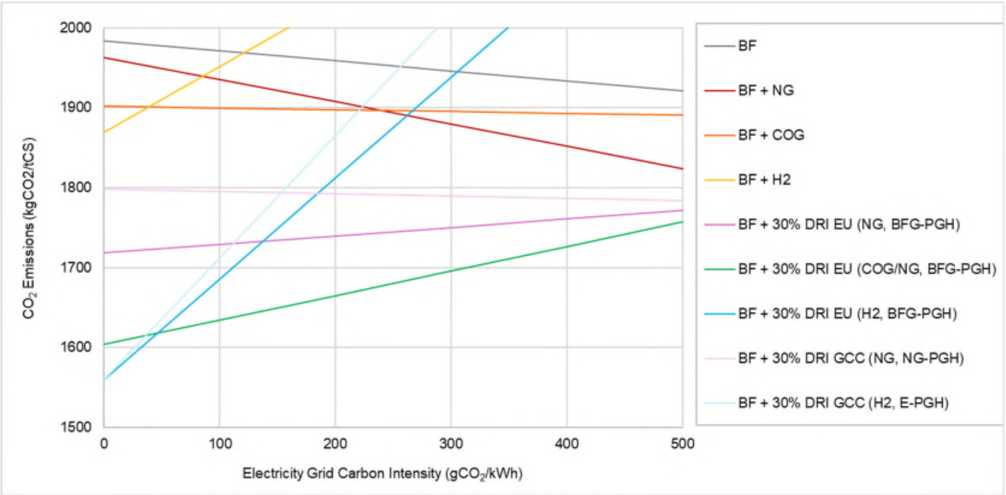

Fig. 5 - Crude Steelmaking Scope 1 and 2 CO_2 Emissions

ECONOMIC ASSESSMENT

The economic analysis is based on the mass and energy balance of the complete steelmaking plant, combined with the cost of raw materials. The price of raw materials and energy are summarized in Table 9.

In the EU scenario DRI is produced on-site in Europe and in GCC scenario DRI is produced in GCC countries and then transported to Europe. The key difference between these two scenario lies in the price of energy and electricity. The raw material prices include freight charges.

Tab. 9 - Price of raw materials for economic analysis

	Unit	**EU**	**GCC**
Green Hydrogen	(€/GJ [€/kg])	47.5 [5.7]	32.5 [3.9]
Natural Gas	(€/GJ [€/kg])	11 [0.54]	4.6 [0.23]
Electricity	(€/kWh)	0.10	0.06

Pellets and hydrogen are treated as purchased inputs in the steel production process. The cost of energy used in the production of these inputs are accounted for within the cost of the pellets and hydrogen themselves. However, from an emissions accounting perspective, the energy consumed during the production of pellets and hydrogen is included in the Scope 2 emissions.

CAPEX is not included in the analysis for the conventional BF-BOF route and configurations with different gas injection in BF. However, for configurations where direct reduced iron (DRI) is produced either on-site or offsite for charging into the blast furnace, an initial investment of €1 billion is assumed for the DRI plant. The annualized CAPEX is calculated based on a 20-year plant lifetime, reflecting the long-term investment cost associated with DRI production infrastructure.

Labour, maintenance, and other operational expenditures are included as part of the operating costs, with different values considered for DRI plants located in the EU and GCC countries.

The implementation of low-carbon technologies often entails higher operating costs compared to conventional blast furnace operations. These cost increases are primarily driven by the use of expensive raw materials and costly low carbon-intensive fuels. As a result, the economic feasibility of adopting such technologies can be challenging under the current status quo.

To address this disparity and provide a comprehensive economic assessment, a carbon tax is considered. This mechanism imposes a cost on CO_2 emissions, thereby improving the economic competitiveness of low-emission alternatives.

Results

The cost distribution for crude steel production via the conventional BF-BOF route is summarized in Figure 6. Electricity is generated as a by-product of the process and excess electricity is exported from the plant. This exported electricity is treated as a credit in the cost analysis, effectively reducing the net production cost of crude steel.

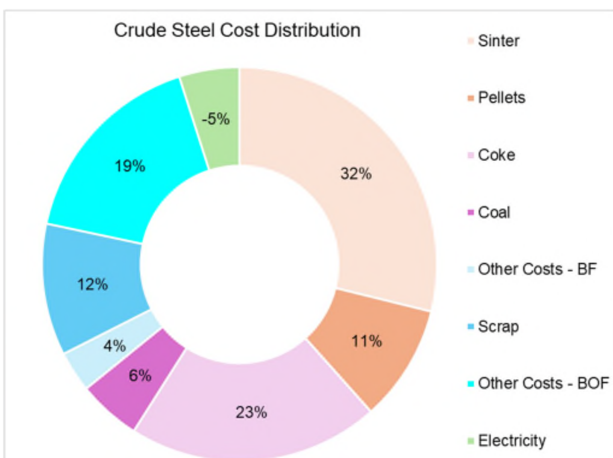

Fig. 6 - Cost distribution of crude steel production for conventional BF+BOF route

Table 10 summarizes the cost of crude steel production for various alternative configurations without carbon tax. COG injection does not significantly increase production costs, but its impact on CO_2 emission reduction is limited. On-site DRI production using COG/BFG is the most attractive option. It offers a notable reduction in CO_2 emissions while having a small impact on the overall cost of crude steel production. Producing DRI offsite in the GCC countries with use of natural gas and transporting it to the EU to charge it in the BF offers stronger economic performance, but results in a smaller reduction in CO_2 emissions compared to on-site DRI production.

Tab. 10 - Cost of steel production without carbon tax for different alternatives

Configurations	Crude Steel Cost without Carbon Tax (€/tCS)
Conventional BF	442
BF + NG	480
BF + COG	447
BF + H2	535
BF + DRI EU (NG, BFG-PGH)	493
BF + DRI EU (COG/NG, BFG-PGH)	490
BF + DRI EU (H2, BFG-PGH)	581
BF + DRI GCC (NG, NG-PGH)	476
BF + DRI GCC (H2, E-PGH)	561

Due to the high cost of hydrogen, hydrogen-based solutions lead to significantly higher crude steel production costs, making them economically uncompetitive compared to alternative methods. Additionally, these solutions require large amounts of electricity to produce hydrogen. When used in regions with high grid carbon intensity, they not only further increase the cost of steel production but also result in higher total Scope 1 and 2 CO_2 emissions.

The cost of crude steel, including carbon tax, is calculated based on a realistic carbon tax rate of 100 €/tCO_2. While Scope 1 emissions remain constant, Scope 2 emissions vary depending on the electricity grid carbon intensity, making total CO_2 emissions sensitive to the electricity balance. In this analysis, electricity grid carbon intensity of 200 gCO_2/kWh is considered, which is close to the EU average.

Figure 7 illustrates the cost of crude steel production across four configurations with the conventional blast furnace (BF) process, using both current electricity and hydrogen prices, as well as reduced future prices assumed to be 50% lower than current levels in both the EU and GCC regions. At the current average electricity price in the EU of 100 €/MWh and with a carbon tax of 100 €/tCO_2 the conventional blast furnace remains cost-effective. This advantage is primarily due to the revenue generated from electricity export, which offsets part of the production cost.

The analysis also indicates that under current high electricity prices, importing DRI from the GCC region to charge in BF is slightly more cost-competitive with on-site production using COG/BFG. However, if electricity prices decrease to a more conservative level of € 50/MWh in the future, utilizing COG/BFG for on-site DRI production and charging it into the blast furnace not only becomes more economically favourable than both importing DRI from the GCC region and producing it on-site using natural gas, but also slightly outperforms the conventional blast furnace process in terms of economic performance. This approach would also lead to a significant reduction in CO_2 emissions.

Importing DRI from the GCC region to charge in BF, where it is produced using hydrogen, is currently not economically viable due to the high cost of hydrogen.

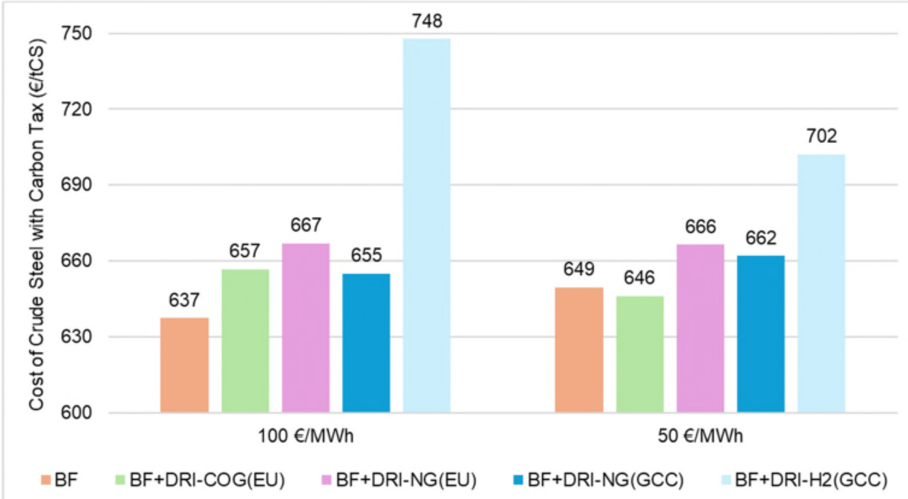

Fig. 7 – Cost of crude steel with carbon tax for different configurations.

On-site production of DRI using COG/BFG, with subsequent charging into the BF becomes increasingly attractive in regions with lower electricity costs, making it not only more sustainable but also economically viable. Moreover, since this configuration results in significantly lower CO_2 emissions compared to the conventional BF, any future increase in carbon taxes would further enhance its economic competitiveness.

CONCLUSIONS

This article evaluated the techno-economic feasibility of two distinct decarbonization strategies for the blast furnace process. The first strategy involves the direct injection of three low carbon intensive fuels (natural gas, coke oven gas, and hydrogen) into the blast furnace. The second explores an alternative approach: producing DRI using these same fuels and subsequently charging it into the blast furnace. This also includes the option of importing DRI from the GCC region, where it is produced using either natural gas or hydrogen.

This assessment clearly demonstrates that, under current market and energy conditions, hydrogen-based steelmaking doesn't offer any economic advantages. Whether used as a reducing agent in the blast furnace or for DRI production, hydrogen's effectiveness is highly constrained by its high cost and the carbon intensity of the electricity grid.

In contrast, producing DRI using COG or Natural Gas and charging it into the blast furnace proves significantly more efficient than direct gas injection. This is largely due to the gas recycling systems in direct reduction plants, which optimize gas utilization and enhance efficiency.

Furthermore, the analysis reveals that producing DRI with natural gas, whether in Europe or the GCC, is less attractive than on-site DRI production using COG. This is primarily due to the higher cost and carbon footprint. If electricity prices trend downward toward 50 €/MWh, on-site DRI production using COG emerges as a most cost-competitive and lower-emission alternative to conventional blast furnace operations.

The path to economically and environmentally sustainable steelmaking lies not in immediate hydrogen adoption, but in strategically leveraging existing process gases like COG especially with current hydrogen price. This approach offers a realistic and impactful transition strategy toward decarbonized steel production.