


Blast furnace decarbonization via gas injection: impacts on costs and CO₂ emissions

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Abstract

The effects of injecting hydrogen, natural gas and coke oven gas into blast furnace tuyeres were analyzed to determine their influence on coke rate reduction, operational costs, and CO₂ emissions. The results indicate that H₂ is the most efficient in coke replacement by mass (1.0-2.0 kg coke/ kg H₂) and offers the highest CO₂ emission reduction but increases production costs. NG shows intermediate replacement ratio (0.8-0.9 kg coke/kg NG), the lowest CO₂ savings and raises production costs. In contrast, COG, despite a lower substitution rate (0.4-0.8 kg coke/kg COG) and intermediate CO₂ emissions reduction, leads to savings in production costs, potentially generating over €6.3 million annually for the analysed blast furnace. According to the study, COG is an economically viable and attractive option for reducing emissions in the Brazilian steel industry.

Keywords: Blast furnace; Gas injection; CO₂ emissions; Production costs.

1 Introduction

Approximately 7-11 % of global carbon dioxide (CO₂) emissions originate from the steel industry, making it one of the largest industrial sources of CO₂ worldwide [1]. This substantial contribution is primarily attributed to the sector's reliance on fossil fuels and energy-intensive processes, particularly in conventional steelmaking routes.

The dominant process for primary steel production is the blast furnace-basic oxygen furnace (BF-BOF) route. The blast furnace (BF) is especially energy-intensive, consuming coke and coal both as fuels and as reducing agents for the conversion of iron ore into hot metal. As a consequence, this process accounts for the majority of CO₂ emissions associated with steelmaking [1]. The combined emissions from blast furnace and basic oxygen furnace operations are estimated to be approximately 1.8 t CO₂ per tonne of crude steel produced [2]. Accordingly, reducing CO₂ emissions from blast furnaces constitutes a core objective in the decarbonization of the steel sector.

A range of strategies is currently being pursued to mitigate CO₂ emissions from blast furnace ironmaking. These include plant modernization, top-gas recycling, increased utilization of biomass-derived reductants, and partial substitution of carbonbased reductants with hydrogen [1]. Among these approaches, the EASyMelt concept offers significant potential

for deep CO₂ emission reduction by eliminating a substantial share of carbon input through the use of externally generated, superheated reducing gas [3]. The EASyMelt concept is a blast-furnace-based ironmaking route targeting ultra-low coke operation by replacing coke with externally produced, superheated H₂-rich syngas and by redistributing the introduction of reducing gases within the furnace.

In parallel, studies have demonstrated the technical feasibility and economic potential of large-scale implementation of carbon capture, utilization, and storage (CCUS) technologies as retrofit solutions for blast furnaces, providing an effective pathway for emission reduction [4]. Alternative ironmaking routes, such as direct reduced iron (DRI) production using natural gas or renewable hydrogen, can achieve CO₂ emission reductions of approximately 33-67 % relative to the BF-BOF baseline; however, widespread deployment is currently constrained by cost challenges [5].

1.1 CO₂ emissions reduction by fuel injection into blast furnaces

Given the continued role of blast furnaces in global steel production, identifying practical measures to reduce their CO₂ emissions is of particular importance.

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One of the most effective short-to medium-term strategies involves the partial substitution of conventional carbon-based fuels, such as coke and pulverized coal, with alternative injectants including hydrogen, natural gas, coke oven gas, and bio-coal.

Pulverized coal injection (PCI) is a well-established technique for reducing coke consumption in blast furnaces. Nevertheless, coal remains a fossil fuel, and its combustion generates significant CO₂ emissions. In contrast, the hydrogen-rich gas injection represents an effective approach for reducing carbon emissions while potentially enhancing productivity [6].

The injection of gaseous fuels such as hydrogen (H₂), coke oven gas (COG), and natural gas (NG) has been widely investigated and industrially demonstrated as a means of reducing CO₂ emissions in blast furnace ironmaking. Owing to their high hydrogen content, these gases can partially replace coke and pulverized coal, thereby lowering the overall carbon intensity of the process. The degree of effectiveness depends on gas composition, injection rate, and composition of the coke to replace. [7].

Hydrogen is a particularly promising reductant, as its use results in the formation of water vapor rather than CO₂. Thermodynamic and process modelling studies indicate that hydrogen injection can substantially reduce both coke consumption and CO₂ emissions.

However, large-scale hydrogen injection is associated with increased energy demand, and the attainable injection rates are constrained by the endothermic nature and kinetics of hydrogen-based reduction reactions, as well as by hydrogen availability [8-10].

Injection of COG increases the hydrogen content of the bosh and tuyere gas, thereby promoting hydrogen-based reduction of iron oxides. This shift enhances indirect reduction by hydrogen at the expense of carbon monoxide, leading to reduced carbon consumption and lower CO₂ emissions. Industrial and pilot-scale studies report measurable reductions in coke rate and improvements in furnace productivity, with COG-to-coke replacement ratios of up to 0.8 kg coke per kg COG [11,12].

Natural gas, composed primarily of methane, is another effective injectant. Its injection introduces both hydrogen and carbon monoxide, which act as less carbon-intensive reductants compared with coke. Natural gas injection has been shown to decrease coke consumption and CO₂ emissions, with the magnitude of reduction depending on the injection rate, gas temperature, and integration with other process optimizations [9,13].

Bio-coal represents an additional option for partially replacing pulverized coal in the injection stream. Industrial trials have demonstrated that substitution levels of up to 10 % are feasible without adverse effects on blast furnace operation, enabling a direct reduction in fossil-derived CO₂ emissions [14].

Overall, modelling, experimental, and industrial studies consistently indicate a considerable potential for CO₂ emission reduction in blast furnace ironmaking through the strategic injection of hydrogen, natural gas, coke oven gas, and biocoal, either individually or in combination with

PCI [6,7,9]. The achievable reduction strongly depends on the degree of fuel substitution, furnace operating conditions, and the integration of injection strategies with other decarbonization technologies.

1.2 CO₂ emissions in Brazilian steel market

Brazil is a major global steel producer, with an annual crude steel output of approximately 36.2 million tonnes in 2021. The BF-BOF route remains the predominant steelmaking technology in the country and is both energy-intensive and responsible for a substantial share of national CO₂ emissions [2,15]. In response to this environmental impact, Brazil has committed to ambitious climate targets, including a 50 % reduction in greenhouse gas emissions by 2030 and the achievement of carbon neutrality by 2050 [15].

Given that a large-scale transition of the Brazilian steel industry from the BF-BOF route to direct reduction technologies is unlikely in the near to medium term, decarbonization efforts must primarily focus on the existing production infrastructure through the implementation of economically viable mitigation measures.

Although the literature proposes multiple pathways for reducing CO₂ emissions in ironmaking, the present study is deliberately limited to evaluating the injection of hydrogen, coke oven gas, and natural gas into blast furnaces. The primary objective is to compare the operational costs associated with each injection strategy and to identify the most advantageous option for application within the Brazilian steel industry.

2 Materials and methods

A mass and energy balance was performed for a reference blast furnace, using raw material and operational data sourced directly from the selected industrial furnace. The following subsections describe the principal assumptions, input parameters, and calculation methodologies employed in the present study.

Several operating scenarios were evaluated, considering the injection of hydrogen, natural gas, and coke oven gas. For each scenario, both a CO₂ emissions analysis and an operational expenditure (OPEX) assessment were conducted, based on utility and fuel costs relevant to the Brazilian steel market.

2.1 Blast furnace parameters

The main operating parameters of the reference BF are summarized in Table 1.

2.2 Coke replacement ratio

The coke replacement ratio is defined as the amount of coke that can be substituted by alternative fuels through tuyere injection. In this study, coke consumption was reduced by introducing hydrogen, natural gas, or coke oven gas while maintaining a constant hot metal production rate.

For each scenario, the PCI rate is fixed to 180 kg/tHM and the target hot metal production rate is kept constant at 10,000 tHM/day. The following coke rates were targeted: 320 kg/tHM (reference case), 310 kg/tHM, 300 kg/tHM and 290 kg/tHM. Some variations around these figures may appear due the mass balance closure.

Injection of hydrogen-rich gases promotes endothermic reactions in the lower furnace, particularly the water-gas within the coke bed. As a consequence, the raceway adiabatic flame temperature (RAFT) decreases with increasing injection rates. If not compensated, excessive RAFT reduction may destabilize furnace operation. Therefore, oxygen enrichment was increased as required to restore RAFT and ensure stable operating conditions during the injection of reducing gases [8,16]. The target RAFT was maintained at approximately 2200 °C; small variations were permitted to achieve convergence of the mass and energy balances.

2.3 Heat and mass balance

The calculations were performed using a blast furnace mass and energy balance framework (MEMO®/BFXpert®). This mass and energy mathematical model allows calculating the operational parameters of a blast furnace and to evaluate its response to various changes in the process conditions. The chemical composition of the injected gases considered in the simulations is given in Table 2.

2.3.1 Model description and assumptions

The MEMO model is a counter-current heat and mass exchanger tool used to quantify gas and solid flows, including the metallic burden, coke, fluxes, injected fuels, and drained liquids. It computes top-gas composition, evaluates the overall thermal balance (reaction heats, sensible enthalpies, heat losses), and supports optimization of blast furnace operating setpoints.

Table 1. Blast Furnace Data

Parameter	Unit	Value
Hot Metal Production	tHM/day	10000
Coke Rate	kg/tHM	320
PCI Rate	kg/tHM	180
Hot Blast Volume	Nm ³ /tHM	800
Hot Blast Temperature	°C	1250
Hot Blast Humidity	g/Nm ³	15
O ₂ Enrichment	Nm ³ /tHM	75

Table 2. Gas chemical composition of injected gases

Gas	H ₂	CO	CO ₂	CH ₄	H ₂ O	N ₂
COG	55%	5%	3%	24%	5%	8%
NG	-	-	0.5%	97.5%	-	2%
H ₂	100%	-	-	-	-	-

Molar percentages.

For modelling purposes, the blast furnace was divided into two zones. The upper section (preparation zone) represents drying, preheating, and pre-reduction of the burden by ascending gases. The lower section (elaboration zone) accounts for solution-loss reactions, final reduction, and melting of iron ore and fluxes to form hot metal and slag.

The energy balance includes sensible enthalpies of all inlet and outlet streams, reaction heats, latent heats, and wall heat losses, which were represented by an overall heat-transfer coefficient. The raceway adiabatic flame temperature is defined as a target thermal condition determined by hot blast properties, oxygen enrichment, injected fuel rates, moisture input, assumed combustion completeness, reaction heats, and resulting gas sensible enthalpies.

The principal model inputs include the following:

- rates and chemical compositions of metallic burden and fluxes.
- dust and sludge streams discharged with top gas.
- heat losses

Below is a non-exclusive list of model outputs:

- rates of coke, blast, oxygen, steam, injected material, slag, hot metal.
- top gas flow rate, temperature, composition, CO and H₂ efficiency.
- hot blast flow rate, oxygen addition, total humidity, temperature.
- tuyere area parameters like gas composition, gas flow rate, flame temperature.

The main reactions considered are:

- $C + O_2 \rightarrow CO_2$ and $C + \frac{1}{2} O_2 \rightarrow CO$ (carbon combustion)
- $C + H_2O \rightarrow CO + H_2$ (steam-carbon reaction)
- $Fuel + O_2 \rightarrow CO/CO_2/H_2/H_2O$
- $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$
- $Iron\ oxide + CO \rightarrow Fe + CO_2$ (indirect reduction)
- $Iron\ oxide + H_2 \rightarrow Fe + H_2O$ (direct reduction by hydrogen)
- $CO_2 + C \leftrightarrow 2CO$ (solution loss reaction)
- $CO + H_2O \leftrightarrow CO_2 + H_2$ (water-gas shift reaction)

- $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$ (CaO combines with SiO_2 , Al_2O_3 into slag components)
- C (in solids/gas) \rightarrow dissolved C in hot metal
- Chemical effects for Si, Al, Mg partitioning

The main model constraints include:

- carbon balance across coke, injected fuels, gaseous and dissolved carbon.
- oxygen balance between blast input and gaseous outputs.
- hydrogen and water balance including fuels, blast moisture and top gas.
- iron balance between burden, hot metal, slag and dust
- slag basicity assuming chemical equilibrium.
- partition of Si, Mn and P in hot metal and slag.
- non-negativity and physical feasibility constraints on flows.

The model is solved iteratively by successive substitution until residuals in all balance equations fall below a convergence tolerance of 1×10^{-6} . The reference case was validated against on-site operational data, showing excellent agreement for coke rate, top-gas composition, and overall furnace performance.

2.3.2 Constraints and feasibility criteria

The following operational constraints were applied in all simulations:

- minimum top-gas temperature (TGT >100 °C).
- RAFT maintained by oxygen enrichment within feasible supply limits.
- no explicit limit imposed on hydrogen content in the top gas.
- no fixed limit on injected fuel rates, assuming compressor capacity can be designed to meet demand.

2.4 OPEX analysis

The costs of the principal raw materials and utilities required for blast furnace operation were obtained from the SMS group database. Because operating expenditure is highly sensitive to raw material prices, a market survey was conducted in 2024 to reflect current Brazilian cost levels. The exchange rate used throughout the study was 1 EUR = 6.2 BRL. The adopted cost assumptions are summarized in Table 3.

Production costs per tonne of hot metal were calculated by multiplying material and utility consumptions obtained from the mass and energy balance by the unit prices in Table 3. These values form the basis for the comparative costeffectiveness assessment of the investigated gas injection strategies.

No explicit CO_2 emission cost was included, as Brazil currently lacks a national carbon pricing mechanism. For comparison, under carbon pricing schemes such as the European Emissions Trading System (EU ETS), where CO_2 prices range from approximately 70-80 €/t, the economic benefits associated with emission reduction would be substantially amplified.

2.5 Calculation of CO_2 emissions

For each scenario, a detailed CO_2 balance was performed based on the results of the heat and mass balance. All material and energy streams entering and leaving the blast furnace system, including hot stoves, were assigned corresponding CO_2 emissions in accordance with ISO 14404. This standard provides a steel-industry-specific framework that accounts for the complex chemical reactions and energy flows inherent to ironmaking processes. Rather than providing a general carbon footprint methodology, it offers a sector-specific framework that accounts for the complex energy flows and chemical reactions unique to iron and steel production. Emission savings are consistently determined for each case and compared to the reference case.

Emission reductions were calculated relative to the reference case. Carbon contents of the principal CO_2 emitting materials were determined from on-site measurements and are summarized in Table 4.

CO_2 emissions resulting from blast furnace gas combustion are not explicitly listed, as they depend on the heating value of the gas, which varies between scenarios. CO_2 emissions were calculated using a conversion factor of 3.66, corresponding to the molar mass ratio of CO_2 to elemental carbon.

Table 3. Raw material and utility costs for Brazilian market

Parameter	Unit	Value
Coke	€/t	300
Pulverized coal	€/t	138
CO_2 (to atmosphere)	€/t	0
O_2	€/Nm ³	0.05
N_2	€/Nm ³	0.20
Demin water	€/m ³	0.76
COG	€/GJ	6.24
NG	€/GJ	27.44
H_2	€/GJ	35.95
Electric power	€/kWh	0.055

3 Results and discussion

The mass and energy balance calculations are presented in Table 5. As anticipated, the results demonstrate that the injection of gaseous fuels through the blast furnace tuyeres leads to a reduction in coke rate. The thermal deficit associated with coke replacement must be compensated by the injected fuel gases and the corresponding increase in oxygen enrichment. However, higher oxygen input reduces the total volume of nitrogen entering the furnace, thereby decreasing the overall gas flow ascending through the burden. As a consequence, the top-gas flow rate decreases, and the top-gas temperature (TGT) is reduced.

The reduction in TGT represents a practical limitation on increasing gas injection rates. To avoid moisture condensation and related operational issues, the TGT should ideally remain above gas dew point, which is function of top gas pressure and top gas moisture content; in the present study, a minimum

value of 100 °C was adopted. Additionally, the higher hydrogen fraction associated with gas injection increases the calorific value of the top gas. While this may be advantageous for downstream energy recovery, close attention must be paid to the resulting gas composition, as elevated hydrogen concentrations can increase the risk of forming flammable or explosive mixtures under certain conditions.

Taking the coke rate as basis for comparison, the gas injection rate (kg/tHM), change in production costs (€/tHM) and CO₂ savings (kg/tHM) are presented in Figures 1, 2 and 3. The results highlight the significant influence of auxiliary fuel injection on blast furnace performance, particularly with respect to coke replacement ratio, production costs, and CO₂ emissions. The coke replacement ratios derived from the slopes shown in Figure 1 indicate that hydrogen provides the highest coke replacement efficiency on a mass basis, followed by natural gas and coke oven gas. These findings are summarized quantitatively in Table 6.

Table 4. CO₂ emissions for raw material and utilities

Material	Unit	C content	Emission
		(t C/unit)	(t CO ₂ /unit)
Coke	t	0.89	3.26
Pulverized coal	t	0.81	2.95
Coke oven gas.	kNm ³	0.21	0.75
Natural gas	kNm ³	0.55	2.02

Table 5. Mass and energy balance for H₂, NG and COG injection

	Unit	Reference case	H ₂ Injection			NG Injection			COG Injection		
			H2 05	H2 10	H2 15	NG 10	NG 20	NG 30	COG 20	COG 40	COG 50
Production	tHM/day	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
Coke rate	kg/tHM	320	311	301	290	312	303	294	310	299	292
PCI rate	kg/tHM	180	180	180	180	180	180	180	180	180	180
COG rate	kg/tHM	0	0	0	0	0	0	0	20	40	50
NG rate	kg/tHM	0	0	0	0	10	20	30	0	0	0
H ₂ rate	kg/tHM	0	5	10	15	0	0	0	0	0	0
O ₂ enrichment	Nm ³ /tHM	75	102	126	125	96	118	132	107	129	129
Hot blast											
Specific rate	Nm ³ /tHM	800	690	580	570	730	650	600	678	591	593
Temperature	°C	1250	1250	1250	1250	1250	1250	1250	1250	1250	1250
RAFT	°C	2210	2210	2200	2100	2210	2210	2190	2210	2180	2130
Top gas											
Vol. flow (dry)	Nm ³ /tHM	1406	1328	1256	1267	1361	1315	1294	1332	1289	1303
LHV (dry)	kJ/Nm ³	3692	4078	4489	4621	3932	4188	4380	4089	4425	4474
TGT	°C	144	117	92	117	130	116	116	119	112	129
CO	vol%	25	26	27	26	26	27	27	26	27	27
CO ₂	vol%	25	25	26	25	25	26	27	26	27	26
H ₂	vol%	5	8	10	13	6	8	9	7	9	10
N ₂	vol%	45	41	37	36	43	39	37	41	37	37
Operational Costs											
Cost Change	€/tHM	-	+17.0	+34.0	+51.1	+9.4	+18.9	+28.3	-0.9	-1.8	-2.2
CO ₂ Emissions											
CO ₂ Savings	kg/tHM	-	-51	-103	-153	-15	-29	-44	-23	-47	-58
Daily Savings	t/day	-	-614	-1232	-1840	-176	-353	-530	-280	-561	-701

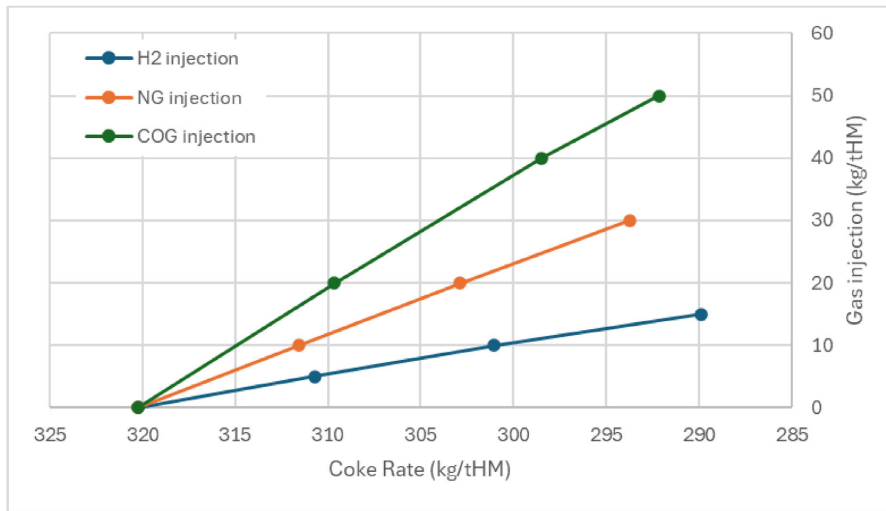


Figure 1. Gas injection rate versus coke rate.

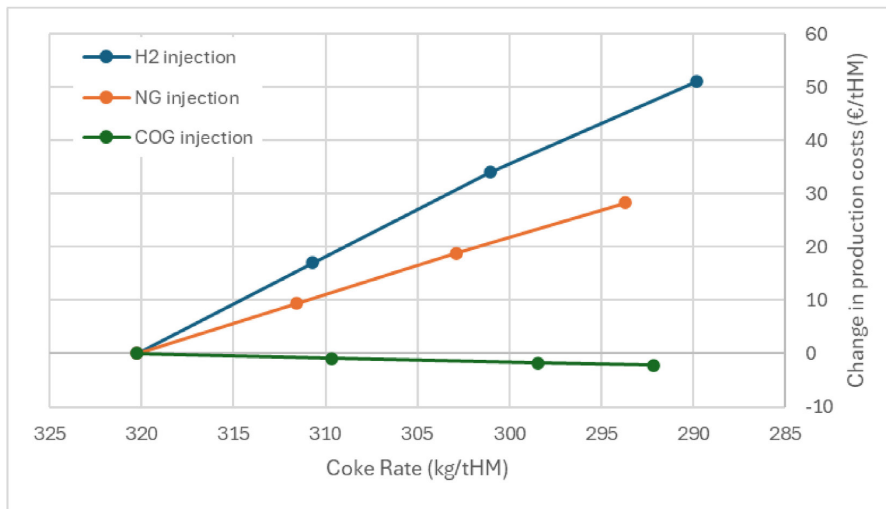


Figure 2. Change in production costs versus coke rate.

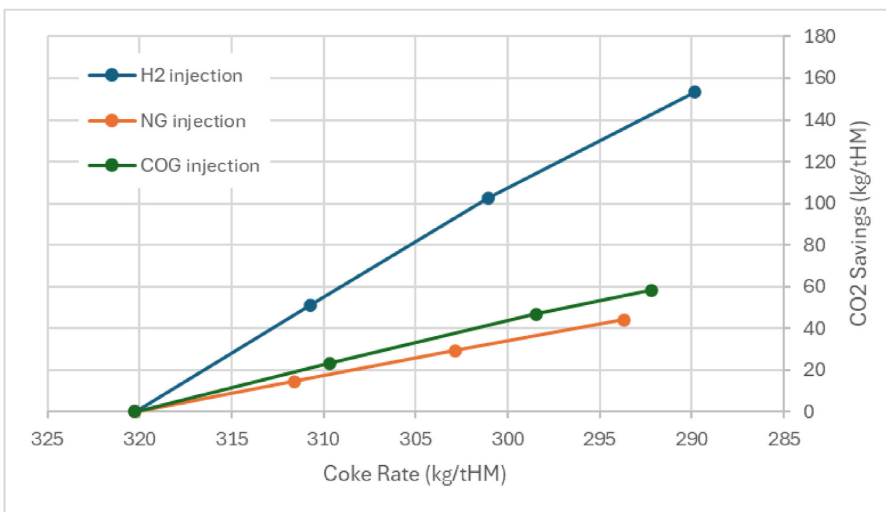


Figure 3. CO₂ savings versus coke rate.

Table 6. Gas replacement ratio, cost savings and CO₂ savings

Gas	Replacement Ratio	Cost Change	CO ₂ Savings
	kg coke/kg gas	€/kg coke	kg CO ₂ /tHM
COG	0.55*	-0.08	58
NG	0.87	+1.08	44
H ₂	1.95	+1.75	153

The economic analysis presented in Figure 2 reveals clear differences among the auxiliary fuels. Injection of hydrogen and natural gas results in a pronounced increase in production costs as coke substitution intensifies. Although these fuels effectively reduce coke consumption, their comparatively high unit costs outweigh the economic benefits associated with coke replacement. This cost penalty represents a major barrier to the large-scale application of hydrogen and natural gas injection in blast furnace operations, particularly at high substitution levels.

In contrast, coke oven gas, as an on-site by-product, offers a substantial economic advantage. Despite its lower replacement ratio (meaning more COG is needed to replace 1 kilogram of coke), its significantly lower effective cost leads to a net reduction in production costs. The calculations indicate that COG injection rates of up to 40 kg/tHM can yield annual savings exceeding € 6.3 million for the analyzed blast furnace.

This result underscores the strong potential of COG injection to enhance the economic performance of blast furnace operations while simultaneously supporting decarbonization objectives. Table 6 further illustrates the impact of each auxiliary fuel on production costs per kilogram of coke replaced, negative values indicate a cost reduction, and positive values indicate a cost increase.

The coke replacement ratio associated with coke oven gas injection is strongly dependent on the relative quality of the injected COG compared with that of the coke being replaced. For instance, high-quality COG with a high calorific value replacing lower-quality coke can result in a high replacement ratio. Conversely, lower-quality COG substituting high-quality coke will lead to a reduced replacement efficiency. It should therefore be emphasized that the replacement ratios reported in this study are specific to the chemical compositions and heating values of the COG and coke considered in the calculations*.

From an environmental perspective, as shown in Figure 3, auxiliary fuel injection provides a clear pathway for reducing CO₂ emissions. Consistent with expectations, hydrogen injection delivers the highest CO₂ savings per kilogram of coke replaced, owing to its ability to generate water vapor rather than CO₂ during iron oxide reduction. Natural gas exhibits the lowest CO₂ savings among the fuels evaluated, reflecting its relatively high carbon content. Coke oven gas demonstrates an intermediate level of CO₂ reduction, consistent with its mixed composition of hydrogen and carbon-containing species. The estimated savings of each gas at 290kg coke/tHM are indicated in Table 6.

These findings indicate that, although all three auxiliary fuels contribute to CO₂ mitigation, their effectiveness differs markedly. Accordingly, the selection of an auxiliary fuel for blast furnace decarbonization should consider not only technical feasibility and coke substitution potential, but also the prevailing economic conditions and the targeted level of CO₂ reduction. Coke oven gas emerges as a particularly attractive option for existing integrated steelworks in Brazil due to its immediate on-site availability and favourable economic performance. In contrast, hydrogen represents a promising long-term solution associated with substantial economic challenges. When compared with COG, natural gas exhibits a comparable potential for CO₂ reduction; however, this benefit is accompanied by a significant increase in production costs.

COG injection increases the hydrogen content of the bosh gas, which reduces its density and viscosity thereby improving gas flow through the burden. The resulting enhancement in gas permeability promotes smoother burden descent and reduces the risk of erratic movement. With better gas permeability pressure drop is also reduced and the coke burning rate is accelerated. As a result, the furnace can operate with higher wind rates, leading to an increase in productivity [11]. Furthermore, the higher hydrogen concentration in the bosh gas provides greater reducing potential, thereby improving overall furnace efficiency.

Despite these advantages, COG injection presents technical challenges. These include condensation risks in the gas pipeline, corrosion under high-pressure conditions, selection of an appropriate compressor technology, and the presence of impurities in COG such as tar, dust, naphthalene, H₂S, and BTX, which necessitate effective gas cleaning and line-purging systems. Consequently, industrial implementation of COG injection requires proven technological solutions and the involvement of experienced and reliable technology providers.

Further research should focus on optimizing injection strategies and exploring the long-term impacts on furnace integrity and product quality for each auxiliary fuel.

3.1 Impact of fuel injection in blast furnace performance

This section discusses the observed effects of injecting different auxiliary fuels on blast furnace operating parameters, considering coke rate reductions in the range of 17-22 kg/tHM. It should be noted that the present calculations are based on theoretical mass and energy balances; depending on the actual operating conditions, a given blast furnace may not be able to accommodate the predicted injection rates in practice.

In industrial operation, fuel injection rates are typically constrained by oxygen availability, top-gas temperature, and top-gas composition. For example, scenario H2-10 may be limited by insufficient TGT, whereas scenario H2-15 may necessitate additional safety measures due to elevated hydrogen content in the top gas. In addition, all investigated cases require oxygen consumption exceeding 40 000 Nm³/h, which could represent a limiting factor depending on the oxygen supply capacity of the steel plant.

Injection of 10 kg/tHM of hydrogen resulted in a coke rate reduction of 19.2 kg/tHM (-6 %). To compensate for the associated thermal deficit, the required oxygen enrichment increased by 51 Nm³/tHM (+68 %). At the same time, the top-gas flow decreased by 149.7 Nm³/tHM (-11 %), while its lower heating value (LHV) increased by 796.9 kJ/Nm³ (+22 %).

Injection of 20 kg/tHM of natural gas led to a coke rate reduction of 17.4 kg/tHM (-5 %). The oxygen enrichment demand increased by 43 Nm³/tHM (+57 %), while the top-gas flow decreased by 90.5 Nm³/tHM (-6 %). The corresponding increase in top-gas LHV was 496.0 kJ/Nm³ (+13 %).

For coke oven gas injection at a rate of 40 kg/tHM, the coke rate was reduced by 21.8 kg/tHM (-7 %). The associated oxygen enrichment increased by 54 Nm³/tHM (+72 %), and the top-gas flow decreased by 116.8 Nm³/tHM (-8 %). In this case, the top-gas LHV increased by 733.2 kJ/Nm³ (+20 %).

Overall, substitution of coke with auxiliary injectant fuels necessitates a comprehensive reassessment of blast furnace operating practices. Such changes significantly affect key parameters, including oxygen enrichment level, raceway size, and thermal conditions in the tuyere-raceway

zone. In addition, auxiliary fuel injection generally results in reduced top-gas volume and temperature, even though the calorific value of the gas may increase.

3.2 Price sensitivity analysis

This section examines the sensitivity of the previously presented results to variations in price assumptions. Table 7 summarizes production cost changes under different scenarios. The first row reproduces the cost variation reported in Table 5, while the subsequent rows present scenarios assuming a 30% decrease (-) and increase (+) in raw material prices. Each row isolates the economic impact of a price variation in a single input, namely coke, oxygen, hydrogen, natural gas, or coke oven gas. The final four rows correspond to carbon pricing scenarios of 20, 50, 75, and 100 €/tCO₂.

The results indicate that, coke oven gas injection continues to yield lower production costs compared with hydrogen and natural gas injection scenarios. Natural gas would only become economically competitive with coke oven gas injection if its price were reduced to roughly 25 % of its present value. Similarly, the hydrogen price would need to decrease to approximately 20 % of its current value to be economically comparable to coke oven gas injection.

If a CO₂ pricing mechanism were introduced in Brazil, the operating costs of all investigated scenarios would become more favourable. Nevertheless, even under such conditions, hydrogen and natural gas injection would still result in increased production costs, whereas coke oven gas injection would continue to reduce overall production costs.

Table 7. Cost change scenarios with raw material price variations

	H2 Injection			NG Injection			COG Injection		
	H2 05	H2 10	H2 15	NG 10	NG 20	NG 30	COG20	COG40	COG50
	Table 5 Values								
€/tHM	+17.0	+34.0	+51.1	+9.4	+18.9	+28.3	-0.9	-1.8	-2.2
Coke									
-30%	+17.9	+35.8	+53.8	+10.2	+20.4	+30.7	+0.1	+0.2	+0.3
+30%	+16.2	+32.3	+48.3	+8.7	+17.3	+25.9	-1.8	-3.7	-4.7
O ₂									
-30%	+16.6	+33.3	+50.3	+9.1	+18.2	+27.4	-1.3	-2.6	-3.0
+30%	+17.4	+34.8	+51.8	+9.8	+19.5	+29.2	-0.4	-0.9	-1.4
H ₂									
-30%	+10.5	+20.9	+31.4	-	-	-	-	-	-
+30%	+23.6	+47.1	+70.7	-	-	-	-	-	-
NG									
-30%	-	-	-	+5.5	+11.0	+16.4	-	-	-
+30%	-	-	-	+13.4	+26.8	+40.2	-	-	-
COG									
-30%	-	-	-	-	-	-	-2.1	-4.2	-5.3
+30%	-	-	-	-	-	-	+0.4	+0.7	+0.9
CO ₂									
20€/t	+16.0	+32.0	+48.0	+9.1	+18.3	+27.4	-1.4	-2.9	-3.7
50€/t	+14.5	+28.9	+43.4	+8.7	+17.4	+26.1	-2.0	-4.1	-5.1
75€/t	+13.2	+26.3	+39.6	+8.3	+16.7	+25.0	-2.6	-5.3	-6.6
100€/t	+11.9	+23.8	+35.7	+8.0	+15.9	+23.9	-3.2	-6.4	-8.1

4 Conclusions

Injection of hydrogen, natural gas or coke oven gas through blast furnace tuyeres demonstrates a substantial potential for reducing CO₂ emissions associated with hot metal production. The results of this study show that while all three auxiliary fuels can be injected at comparable coke rates, their performance differs significantly with respect to coke replacement efficiency, production costs, and CO₂ emission reduction.

The coke replacement ratio varies among the investigated gases, with hydrogen exhibiting the highest replacement efficiency, followed by natural gas and coke oven gas. From an economic perspective, however, both hydrogen and natural gas injection lead to increased production costs, despite their ability to reduce coke consumption. In contrast, coke oven gas emerges as a financially advantageous option. Its on-site availability and comparatively low effective cost enable a reduction in overall operating expenditure, even at higher substitution levels. For the analyzed blast furnace, injection of up to 40 kg/tHM of COG could generate annual savings exceeding € 6.3 million.

With respect to environmental performance, hydrogen injection provides the greatest CO₂ emission reduction, achieving savings of up to 153 kg CO₂/tHM. Natural gas injection yields the lowest CO₂ savings, approximately

44 kg CO₂/tHM, reflecting its relatively high carbon content. Coke oven gas offers an intermediate level of emission reduction, approximately 58 kg CO₂/tHM, consistent with its mixed hydrogen and carbon-based composition.

Considering the specific context of the Brazilian steel industry, which is dominated by the BF-BOF route and faces stringent decarbonization targets, coke oven gas represents a particularly attractive and immediately implementable solution [17,18]. Its availability within integrated steelworks and its favorable economic impact make it a key option for short and medium-term decarbonization strategies. Although hydrogen holds considerable promise for deep decarbonization, significant challenges related to production cost, supply infrastructure and availability remain to be resolved. Natural gas, by comparison, delivers limited emission reduction while increasing production costs, owing to its elevated price in the Brazilian market.

Overall, the investigated auxiliary fuel injection strategies can enable meaningful reductions in blast furnace CO₂ emissions and contribute to the steel sector's decarbonization objectives. Future research should focus on optimizing injection strategies, integrating auxiliary fuel injection with other emission-reduction technologies and assessing long-term impacts on furnace integrity, operational stability and product quality.

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