



# High oxygen and SNG injection in blast furnace ironmaking with Power to Gas integration and CO<sub>2</sub> recycling

Jorge Perpiñán<sup>a,\*</sup>, Manuel Bailera<sup>a</sup>, Begona Peña<sup>a</sup>, Luis M. Romeo<sup>a</sup>, Valerie Eveloy<sup>b</sup>

<sup>a</sup> Escuela de Ingeniería y Arquitectura, Universidad de Zaragoza, María de Luna 3, 50018, Zaragoza, Spain

<sup>b</sup> Khalifa University, Department of Mechanical Engineering, United Arab Emirates

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## ABSTRACT

In the last years, reduction of CO<sub>2</sub> emissions from the steel industry has been of great importance. Carbon capture, oxygen blast furnaces and top gas recycling technologies, among others, have been deeply studied as low carbon solutions. In this paper, a novel integration of carbon capture and power to gas technologies in the steelmaking industry is presented. Green hydrogen via proton exchange membrane (PEM) electrolysis and CO<sub>2</sub> via methyldiethanolamine (MDEA) scrubbing from the blast furnace gas (BFG) are used to produce synthetic natural gas in an isothermal fixed bed methanation plant. The latter gas is injected into the blast furnace, closing a carbon loop and reducing coal consumption. The oxygen by-produced in the electrolyser covers the entire oxygen demand of the steelmaking plant and avoids the need for an air separation unit (ASU). The novelty of this work relies on the variation of the oxygen enrichment and its temperature in the hot blast, and how it influences the power to gas integration concept. This power to gas integration is compared with a conventional BF-BOF plant from a technical, economic, energy and environmental point of view. Both plant process configurations were implemented in Aspen Plus simulations, assessing the fossil fuel demand, energy penalty, cost and CO<sub>2</sub> emissions. Emission reduction up to 34% can be achieved with power to gas integration, with an energy penalty of 17 MJ/t<sub>HM</sub> and a cost of 352 €/tCO<sub>2</sub>.

## 1. Introduction

An essential goal in the transition toward a sustainable energy system is to decarbonize conventional energy systems. The Paris Agreement in 2015 targets a maximum increase of the world average temperature of 1.5–2.0 °C compared with the pre-industrial revolution period, and 80–95% cut in greenhouse gas (GHG) emissions in Europe compared with the level in 1990 (European Commission, 2022).

The industry accounts for 40% of global CO<sub>2</sub> emissions, according to (Intergovernmental Panel on Climate Change (IPCC), 2022), and the iron and steel (I&S) sector for up to 27% of the global manufacturing sectors (International Energy Agency, Iron and Steel Technology Roadmap., 2020). Consequently, improving overall energy efficiency and reducing primary energy consumption should be high priorities of the I&S sector, especially in times of high energy competitiveness and energy dependency.

Steel is mainly produced by three routes: (i) blast furnace-basic oxygen furnace (BF-BOF), with 70% share of steel world production; (ii)

scrap-electric arc furnace (scrap-EAF), with 23% share; and (iii) direct reduced iron-electric arc furnace (DRI-EAF), with 7% share. Among the three routes, the BF-BOF is the largest specific energy consumer (21–23 GJ/t<sub>HM</sub>) and the largest CO<sub>2</sub> emitter (2.0–2.2 tCO<sub>2</sub>/t<sub>HM</sub>) (International Energy Agency, Iron and Steel Technology Roadmap., 2020). Regarding the fuel consumed by each route, the BF-BOF is mainly based on coal, while the DRI-EAF consumes NG, H<sub>2</sub> and electricity, and the scrap-EAF consumes mostly electricity.

Reduction of CO<sub>2</sub> emissions from the BF-BOF route in the I&S industry has been the topic of extensive research. The transition to low carbon BFs started in the 1960s, combining oil injection and oxygen enrichment, hitting today's advanced oxygen blast furnaces (OBFs). Throughout this transition, different technologies have been used, such as pulverised coal injection (PCI), hot reducing gas derived from the reforming of COG or oil, OBFs with massive PCI, low-temperature BF, high reactivity coke BF, charcoal blast furnace (Andrade de Castro et al., 2005), top gas recycling (TGR), and advanced OBF. The TGR process is commonly studied in an OBF and includes CO<sub>2</sub> sequestration prior to reusing the top gas, in order to get rid of the N<sub>2</sub> and CO<sub>2</sub> before the

\* Corresponding author.

E-mail addresses: [jorge.perpinan@unizar.es](mailto:jorge.perpinan@unizar.es) (J. Perpiñán), [mbailera@unizar.es](mailto:mbailera@unizar.es) (M. Bailera), [bpp@unizar.es](mailto:bpp@unizar.es) (B. Peña), [luismi@unizar.es](mailto:luismi@unizar.es) (L.M. Romeo), [valerie.eveloy@ku.ac.ae](mailto:valerie.eveloy@ku.ac.ae) (V. Eveloy).

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Nomenclature			
<i>Abbreviation meaning</i>			
AFT	Adiabatic Flame Temperature	GHG	Green House Gas
ASU	Air Separation Unit	HM	Hot Metal
AHF	Air Heating Furnace	I&S	Iron and Steel
BF-BOF	Blast Furnace-Basic Oxygen Furnace	IEA	International Energy Agency
BFG	Blast Furnace Gas	LHV	Lower Heating Value
BOFG	Basic Oxygen Furnace Gas	MDEA	Methyldiethanolamine
CC	Carbon Capture	PEM	Proton Exchange Membrane
CCUS	Carbon Capture Utilization and Storage	PtG	Power to Gas
COG	Coke Oven Gas	PCI	Pulverised Coal Injection
DRI	Direct Reduced Iron	PFD	Process Flow Diagram
EAF	Electric Arc Furnace	SNG	Synthetic Natural Gas
		tHM	Ton of Hot Metal
		tCS	Ton of Crude Steel
		$\alpha, \beta, \gamma$	Parameters for Economic Analysis

tuyere or shaft injection. The concept of advanced OBF (Sato et al., 2015), takes advantage of a preheated gas injection in the upper shaft, allowing for reductant flexibility, i.e. intensified natural gas injection, high PCI or other reducing agents (Ariyama et al., 2016). Additionally, the nitrogen-free condition in the OBF contributes to the acceleration of the reduction rate and increased productivity. International projects such as ULCOS-BF (Abdul Quader et al., 2016) and COURSE50 (Tonomura, 2013) aim to apply carbon capture (CC) from the blast furnace gas (BFG) through physical adsorption and chemical absorption, where the CO<sub>2</sub> is sent to storage, and the clean gas is recycled to the OBF (TGR). Most OBF-TGR studies focus on CO recycling, leading to a marked reduction of energy content for downstream gases for plant use (Sahu et al., 2015), and although great emission reduction can be achieved, it may not fulfil downstream energy requirement needs, which is one of the main challenges presented for this kind of configurations.

Some drawbacks of CC technology are the need for geological storage (Perpiñán et al., 2022a,b) or the need for large-scale and long-term carbon utilization (Mac Dowell et al., 2017). Recent steel roadmaps refer to smart carbon avoidance or carbon capture and re-use (CCU) as one of the routes to lower carbon emissions (ArcelorMittal, 2023). This is where Power to Gas (PtG) stands out as a promising alternative, as reduces CO<sub>2</sub> emissions while providing additional benefits (Bailera et al., 2017a; 2017b, 2021a, b). The PtG concept involves processes that convert renewable electricity into synthetic gaseous fuels, primarily H<sub>2</sub>. This green gas can be an intermediate or a final energy carrier. If combined with CO<sub>2</sub> in a methanation reactor, synthetic natural gas (SNG) is obtained (i.e., Power to Methane) (Romeo et al., 2020). If this SNG is used again in the I&S industry, the CO<sub>2</sub> is being recycled and used constantly, thus not being emitted to the atmosphere or stored underground. Another additional benefit of PtG technology is the reduction of fossil fuel consumption since it is substituted by SNG.

Only a few studies have been found in the literature on Power to Gas and carbon capture integration in the BF-BOF route (Bailera et al., 2022a,b; Bailera et al., 2021a,b, 2022a,b; Perpiñán et al., 2022a,b). Different configurations have been approached while integrating PtG technology, such as biomass methanation (Rosenfeld et al., 2020), OBF (Perpiñán et al., 2021), TGR and SOEC electrolysis (Hisashige et al., 2019), obtaining a wide range of results. CO<sub>2</sub> emission reduction in the BF varies from 6% to 21%, injecting up to 115 kg<sub>SNG</sub>/t<sub>HM</sub> in the BF.

The present work assesses the performance and cost of a PtG-steelmaking integration, where green H<sub>2</sub> is produced in a PEM electrolyser, CO<sub>2</sub> is captured by amine scrubbing from the BFG, and SNG is produced via catalytic isothermal methanation from the two previous components. The SNG is injected into the BF, keeping the CO<sub>2</sub> in a closed loop, reducing emissions and avoiding geological storage. This configuration focuses on CO<sub>2</sub> recycling instead of on CO recycling (TGR), thus ensuring enough energy content for downstream processes. The oxygen by-produced in the electrolyser covers the oxygen demand of the

industry, eliminating the air separation unit (ASU). This PtG-steelmaking integration is studied by varying the oxygen enrichment in the hot blast and its temperature, and the results are compared with a conventional BF-BOF plant in terms of fossil fuel demand, energy penalty and CO<sub>2</sub> emissions. Both simulations, the conventional and the PtG integration, have been undertaken using Aspen Plus software. Lastly, an economic evaluation of the PtG-steelmaking integration is carried out to determine the specific costs of this novel integration.

## 2. Case studies

In order to assess the improvement of the proposed low-carbon concept, a conventional steelmaking plant with a production of 320 t<sub>HM</sub>/h (Steelmaking Technologies. CISDI Ingeniering CO. LTD, 2022) is assumed as a base case of Fig. 1a. Conventional BF-BOF plants consist of a coke oven, blast furnace and hot stoves, sinter strand, basic oxygen furnace, ASU, the casting and rolling stage and a combined cycle power plant. The inputs to the system are the iron ore in the sinter strand; the coal in the sintering, coke oven and blast furnace; and scrap in the BOF. The by-produced energetic gases of the industry (COG, BFG and BOFG) are used as fuel in different processes. The power plant is sized with 100 MWe net power (Wu et al., 2016), consuming part of the available COG, BOFG and BFG, generating enough electricity for the industry, making it self-sufficient. The remaining gases not used in the power plant or other processes are supposed to be sold to nearby industries.

The proposed PtG-steelmaking integration is shown in Fig. 1b. This case adds a PEM electrolyser to produce H<sub>2</sub>, an amine scrubbing to capture CO<sub>2</sub>, and a methanation plant to produce synthetic natural gas. The CO<sub>2</sub> is captured from the BFG, and the SNG is continuously injected into the BF, recycling the CO<sub>2</sub> and closing a carbon loop. It is expected that enough energy content meets the needs of the downstream processes, CO<sub>2</sub> emissions are lowered, and geological storage is not needed. The O<sub>2</sub> by-produced in the electrolyser is used to feed the BOFG demand, avoiding the ASU, and is also used to enrich the blast furnace's hot blast. The excess of oxygen is supposed to be sold. The hot blast enrichment is studied gradually, from 21 vol% O<sub>2</sub> to 95 vol% O<sub>2</sub> in the hot blast, obtaining an oxygen blast furnace (OBF) as a result. The influence of the oxygen temperature has also been studied, at 25 °C and 1200 °C. With this technology, we are able to indirectly electrify the BF-BOF steel industry to some extent.

## 3. Methodology

The process models of the conventional I&S plant and the PtG-steelmaking integration were implemented in Aspen Plus v11. The process flow diagrams in Fig. 1 show the hierarchy blocks for the conventional I&S industry and the PtG-steelmaking integration. Each hierarchy block combined the necessary sub-models to faithfully reproduce

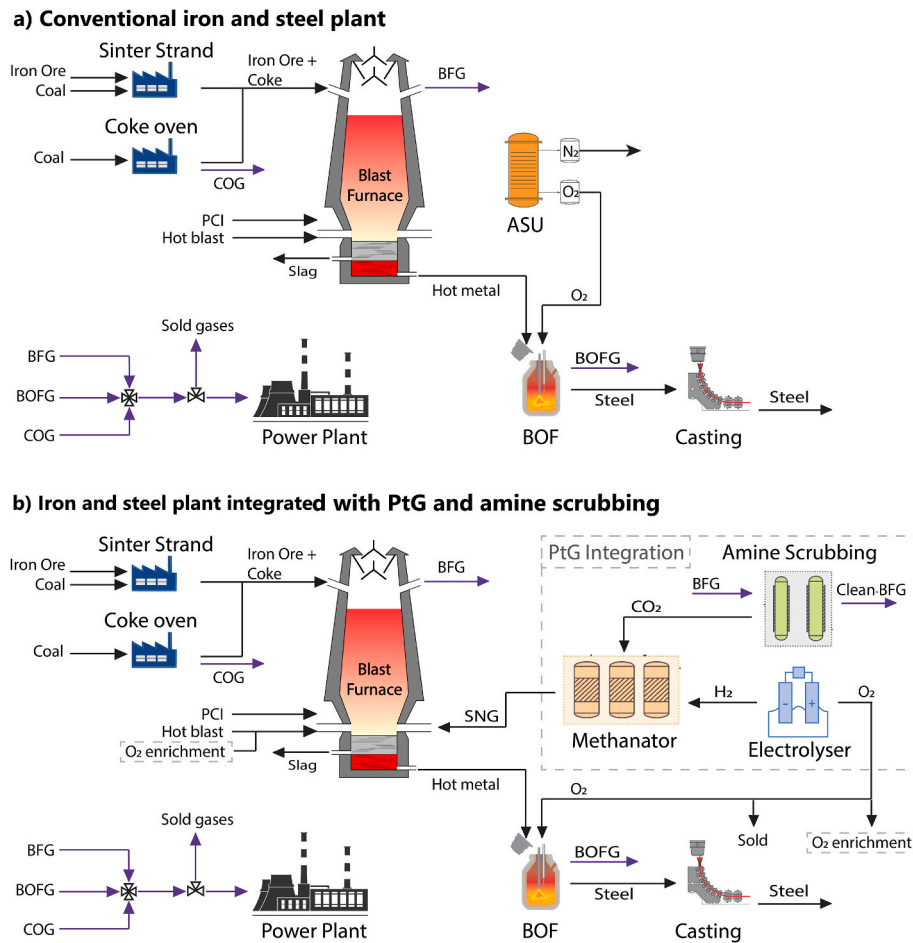


Fig. 1. Process flow diagram for a) conventional iron and steel plant and b) its integration with power to gas and carbon capture (dashed rectangle).

every process and works with its own Aspen property method (Aspen Technology Inc, 2019c). The sinter strand represents the agglomeration of fine ore particles. The coke oven simulates the coke-making process, with COG as a by-product. The blast furnace hierarchy comprises a simplified version of a blast furnace process that reduces the iron ore forming hot metal and BFG. The hot blast temperature is 1200 °C. Some additional parameters of the BF, such as top gas composition and temperature, air and coke flow rates, CO utilization (Eq. (1)) and the AFT, were externally calculated through a revised Rist diagram (Bailera et al., 2021a,b). The H<sub>2</sub> utilization is fixed at 0.47 (Eq. (2)) (A. Babich, D. Senk, H. W. Gudenau, 2008) and the efficiency of the furnace stack is 0.9. The BOF converts the hot metal to steel, reducing the carbon content from 4.5 wt% C to 0.267 wt% C. The ASU was directly taken from the Aspen repository (example block Power, Coal gasification, IGCC (Aspen Technology Inc, 2019b)). For the I&S production blocks and the ASU, the PENG-ROB property method was used. The power plant is a combined cycle sized at 100 MWe net power (Wu et al., 2016), modelled using the PR-BM property method. The amine scrubbing model captures 90% of the inlet CO<sub>2</sub>, using methyldiethanolamine (MDEA) as solvent. The PEM electrolyser generates O<sub>2</sub> and H<sub>2</sub> with an energy consumption assumed at 3.8 kWh/Nm<sup>3</sup> (Salehmin et al., 2022). Both the amine scrubbing and the electrolyser use the ELECNRTL property method. The methanation plant consists of two isothermal fixed-bed reactors working at 300–350 °C and 5 bar (Izumiya and Shimada, 2021; Rönisch et al., 2016) that reach a SNG purity of 95 vol% CH<sub>4</sub>, with the SRK property method. Stoichiometric conditions are considered for the methanation reaction, with a H<sub>2</sub>:CO<sub>2</sub> ratio of 4. More details about the methodology, the simulation processes and the Aspen Plus model of the base case can be found in (Perpiñán et al., 2022).

$$\mu_{CO} = CO_2 / (CO_2 + CO) \quad (1)$$

$$\mu_{H_2} = H_2O / (H_2O + H_2) \quad (2)$$

Although secondary processes (i.e., hot blast heating (also called hot stoves), SNG heating, other heating and combustion processes and CO<sub>2</sub> emission streams) are not represented in Fig. 1, they are taken into account and modelled in the Aspen model. Sub-sections 3.1 to 3.6 state the fundamental changes compared to previous works (Perpiñán et al., 2022a,b).

### 3.1. Preheating gas injection

The decreased bosh gas volume in the OBF, caused by the lack of nitrogen, causes that preheating of the burden in the upper part tends to be insufficient in comparison with the conventional BF, which leads to low BFG temperature. If this temperature drops below 100 °C, this can generate significant problems regarding water condensation. In order to compensate for the insufficient heat supply in the shaft, it is necessary to inject preheating gas into the upper shaft. A fuel (usually BFG) is burned with pure oxygen and the flue gas is injected at 1000 °C in the upper part of the BF. Fig. 2 (Ariyama et al., 2016; Sato et al., 2015) shows the evolution of the blast furnace towards reductant flexibility and carbon dioxide mitigation, from a conventional BF to an advanced OBF with pure oxygen and preheating gas injection.

### 3.2. Distribution of energetic gases

The energetic gases (BOFG, COG and BFG) are distributed in

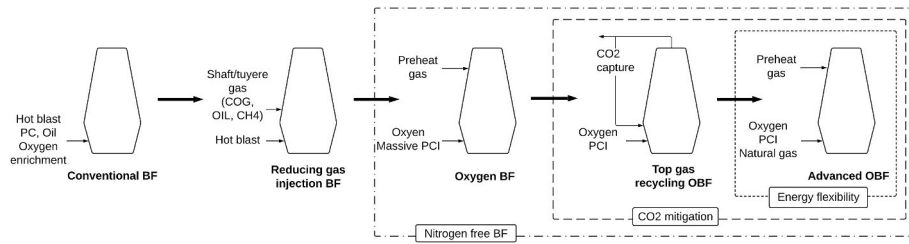


Fig. 2. Evolution of blast furnace for reducing coke rate and CO<sub>2</sub> emissions. Adapted from (Ariyama et al., 2016).

different processes. BFG is supplied to the sinter strand, the hot stoves and the power plant, BOFG is supplied to the casting stage and the power plant, and the COG is supplied to the coke oven, BOF and the power plant. As mentioned before, a certain amount of these gases is sold to nearby industries.

For the PtG-steelmaking integration, the distribution of the energetic gases remains almost the same, but with some changes in the BFG distribution, see Fig. 3. The raw BFG is used as preheating gas in the BF and the amine scrubbing stage. After this stage, the clean-BFG is mixed with the rest of the BFG, and is used in the processes mentioned before (sinter strand, hot stoves and power plant) but also to heat the SNG to 700 °C before injecting it into the BF (Perpiñán et al., 2022a,b).

### 3.3. Oxygen temperature for hot blast enrichment

Oxygen injection in blast furnaces is usually heated together with the atmospheric air in the hot stoves for concentrations up to 30% O<sub>2</sub>. This temperature is around 1200 °C. For higher enrichments, the oxygen is injected after the hot stoves, at atmospheric temperature (25 °C) (R. Li et al., 2022; Tsupari et al., 2015). Nie et al. (2021) and Sato et al. (2015) describe that oxygen enrichment exceeding 30% can cause safety problems and equipment damage in conventional existing hot stoves.

However, Sahu et al. (2015) preheats a 45% oxygen-enriched hot blast to 1200 °C, Zhang et al. (2017) simulates 98% pure oxygen at 500 °C, and Kim et al. (2016) experimentally preheats pure oxygen to 650 °C (in the glass industry), but none of this works clarifies if higher temperatures can be reached.

Since the temperature limit of pure oxygen is not clear, and no information was found regarding potential technical limitations in new equipment, two different cases are investigated in this study: oxygen enrichment at atmospheric temperature (25 °C), and oxygen enrichment preheated to 1200 °C.

### 3.4. Sizing of the PtG plant

For the PtG-steelmaking integration, the oxygen enrichment in the hot blast increases from 21% (atmospheric air) to 95%. For each point, the maximum amount of SNG is injected, firstly to reduce the pulverised

coal injection (PCI) and once it is over, to substitute the coke rate. The amount of SNG is limited by the adiabatic flame temperature (AFT), which should not be dropped below 2000 °C for technical reasons (Peacey and Davbenport, 1979). Consequently, the oxygen enrichment increases the AFT and the SNG injection lowers it, reaching an equilibrium of 2000 °C in the AFT for each point of the oxygen enrichment. Then, the AFT (2000 °C), the oxygen enrichment (21–95%) and the oxygen temperature (25 or 1200 °C) are inputs to the model, while SNG, coal, coke and BFG mass flow rates are outputs to the model. Thus, knowing the amount of SNG required for each point, the methanation plant, the amine scrubbing plant and the PEM electrolyser can be sized. The oxygen by-produced in the electrolyser is used to eliminate the ASU and to feed the BOF and hot blast enrichment necessities.

### 3.5. Coal-equivalent replacement ratio (coal-e RR) and energy penalty

The coal-e RR is defined as the net coal replaced by the synthetic natural gas (SNG) injected (Eq. (3)). The net coal is the sum of the PCI and the coking coal needed for coke making.

$$Coal - e RR = \frac{\Delta \dot{m}_{PCI} + \Delta \dot{m}_{CokingCoal}}{\Delta \dot{m}_{SNG}} [kg_{Coal} / kg_{SNG}] \quad (3)$$

The energy penalty is defined as the net energy consumed in the industry per kg of CO<sub>2</sub> avoided with the PtG-steelmaking integration (Eq. (4)).

$$E_{penalty} = \frac{\Delta E_{cons} - \Delta E_{coal} \cdot \eta_{elec} - \Delta E_{gases} \cdot \eta_{elec}}{\Delta \dot{m}_{CO_2}} [MJ / kg_{CO_2}] \quad (4)$$

Where  $\Delta E_{cons}$  is the electricity consumed in the industry (MJ/t<sub>HM</sub>),  $\Delta E_{coal}$  is the coal energy avoided (MJ/t<sub>HM</sub>),  $\Delta E_{gases}$  is the excess of gases sold to nearby industries,  $\eta_{elec}$  is the energy conversion factor from coal to electricity (0.33) and  $\Delta \dot{m}_{CO_2}$  is the amount of CO<sub>2</sub> avoided kg<sub>CO<sub>2</sub></sub>/t<sub>HM</sub>. All these parameters are concerning the conventional iron and steel plant and the PtG-steelmaking integration.

### 3.6. Economic analysis

The economic analysis was performed for the investment required for the PtG-steelmaking integration, i.e., implementing the PEM, methanation stage and amine scrubbing. A 4% interest for the discount factor is assumed (Eq. (5)), with a loan amortization of 20 years. The PtG system is assumed to operate 8000 h per year (Bailera et al., 2017a; 2017b), a carbon tax value of 84.28 €/t<sub>CO<sub>2</sub></sub> (Sendeco2, 2022) and a renewable electricity consumption cost of 77 €/MWh are assumed. The initial capital expenditure (CAPEX) for the PtG integration is composed of the amine, electrolysis and methanation plants, the heat exchangers network, the BF retrofitting, and other direct and indirect costs. The annual operational expenditure (OPEX) is composed of the catalyst renovation, the water consumed by the electrolyser, the amine renovation, the purchased electricity and the operation and maintenance (O&M). The annual incomes are the saved CO<sub>2</sub> taxes and coal, and the sold steel gases (BFG, BOFG and COG) and oxygen, see Table 1. The specific cost, in €/t<sub>CO<sub>2</sub></sub> and €/t<sub>HRC</sub>, is shown in Eq. (6) and Eq. (7).

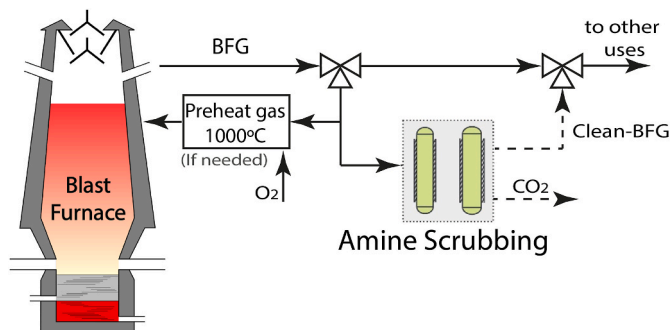


Fig. 3. Process flow diagram for BFG distribution in the PtG-steelmaking integration.

**Table 1**  
Data for the economic analysis of the PtG integration in the iron and steel industry.

	Cost equation (M€) or (M€/y)	Parameters $\alpha, \beta, \gamma$	Ref.
<b>CAPEX</b>			
Amine Plant			
Overall Cost	$26.094 \cdot (\alpha/408)^{0.65}$	$\alpha = \text{CO}_2$ captured [t/h]	Abu-Zahra et al. (2007)
Electrolysis			
Overall Cost	$400 \cdot 10^{-6} \cdot \alpha$	$\alpha = \text{Power}$ [kW]	TURNER (2022)
Methanation			
H <sub>2</sub> compressor	$0.267 \cdot (\alpha/445)^{0.67}$	$\alpha = \text{Power}$ [kW]	De Saint Jean et al. (2015)
CO <sub>2</sub> compressor	$0.267 \cdot (\alpha/445)^{0.67}$	$\alpha = \text{Power}$ [kW]	De Saint Jean et al. (2015)
Reactors	$300 \cdot 10^{-6} \cdot \alpha$	$\alpha = \text{SNG power}$ [kW <sub>SNG</sub> ]	Lehner et al. (2014)
Catalyst	$0.1875 \cdot \alpha$	$\alpha = \text{Volume of catalyst}$ [m <sup>3</sup> ]	De Saint Jean et al. (2015)
Heat exchangers	$(9016.3 + 721.3 \cdot (\alpha^{0.8})) \cdot 10^{-6}$	$\alpha = \text{Area}$ [m <sup>2</sup> ]	(Aspen Technology Inc, 2019a)
BF retrofitting	$0.5 \cdot \alpha$	$\alpha = \text{BF construction cost}$	(IEA - Iron & Steel Roadmap, 2020)
<b>Other direct costs</b>			
Installation	$10\% \cdot \alpha$	$\alpha = \text{Total equipment costs}$ [M€]	Abu-Zahra et al. (2007)
Instrumentation & control	$4\% \cdot \alpha$	$\alpha = \text{Total equipment costs}$ [M€]	Abu-Zahra et al. (2007)
Piping	$16\% \cdot \alpha$	$\alpha = \text{Total equipment costs}$ [M€]	Abu-Zahra et al. (2007)
Electrical	$5\% \cdot \alpha$	$\alpha = \text{Total equipment costs}$ [M€]	Abu-Zahra et al. (2007)
Building	$5\% \cdot \alpha$	$\alpha = \text{Total equipment costs}$ [M€]	Abu-Zahra et al. (2007)
Land	$1\% \cdot \alpha$	$\alpha = \text{Total equipment costs}$ [M€]	Abu-Zahra et al. (2007)
<b>Indirect costs</b>			
Engineering	$7\% \cdot \alpha$	$\alpha = \text{Total direct costs}$ [M€]	Abu-Zahra et al. (2007)
Legal expenses	$2\% \cdot \alpha$	$\alpha = \text{Total CAPEX}$ [M€]	Abu-Zahra et al. (2007)
Construction expenses	$4\% \cdot \alpha$	$\alpha = \text{Total CAPEX}$ [M€]	Abu-Zahra et al. (2007)
Contingency	$7\% \cdot \alpha$	$\alpha = \text{Total CAPEX}$ [M€]	Abu-Zahra et al. (2007)
<b>OPEX</b>			
Amine renovation	$3204 \cdot 10^{-6} \cdot \alpha$	$\alpha = \text{MDEA renovation}$ [t <sub>CO2</sub> /y]	Kohl and Nielsen (1997)
Catalyst renovation	$15\% \cdot \alpha$	$\alpha = \text{Initial catalyst cost}$ [M€]	Bailera et al., 2017a; 2017b
Electricity	$\alpha \cdot \beta \cdot \gamma \cdot 10^{-6}$	$\alpha = \text{Electricity purchased}$ [MWh/t <sub>HM</sub> ·h <sup>-1</sup> ], $\beta = \text{Operating hours}$ [h/y], $\gamma = \text{Electricity cost}$ [€/MWh]	-
Water	$1.47 \cdot 10^{-6} \cdot \alpha$	$\alpha = \text{Water consumption}$ [m <sup>3</sup> /y]	Benjaminsson et al. (2013)
O&M	$3\% \cdot \alpha$	$\alpha = \text{Total CAPEX}$ [M€]	Abu-Zahra et al. (2007)
<b>INCOMES</b>			
Coal	$130.43 \cdot 10^{-6} \cdot \alpha$	$\alpha = \text{Coal saved}$ [t <sub>Coal</sub> /y]	(Quarterly Coal Report July–September 2021. U.S.

**Table 1 (continued)**

	Cost equation (M€) or (M€/y)	Parameters $\alpha, \beta, \gamma$	Ref.
Oxygen	$80 \cdot 10^{-6} \cdot \alpha$	$\alpha = \text{O}_2$ generated [t <sub>O2</sub> /y]	Department of Energy, 2021)
CO <sub>2</sub> taxes	$84.28 \cdot 10^{-6} \cdot \alpha$	$\alpha = \text{CO}_2$ saved [t <sub>CO2</sub> /y]	Hurskainen (2017)
Steel gases	$(15 + \alpha \cdot \beta / 13) \cdot 10^{-6} \cdot \gamma$	$\alpha = \text{Natural gas price}$ [€/MWh] $\beta = \text{Steel gases LHV}$ [kWh/kg] $\gamma = \text{Steel gases generated}$ [MWh/y]	(Sendeco2, 2022)

$$D_{coeff} = \frac{1}{(1+i)^n} \tag{5}$$

$$Specific\ Cost = \frac{\left(\frac{Capex}{Loan\ amortization} + Opex - Incomes\right) \cdot 10^6}{CO_2\ avoided \cdot Operating\ hours} \left[ \frac{\text{€}}{t_{CO_2}} \right] \tag{6}$$

$$Specific\ Cost = \frac{\left(\frac{Capex}{Loan\ amortization} + Opex - Incomes\right) \cdot 10^6}{Steel\ Production \cdot Operating\ hours} \left[ \frac{\text{€}}{t_{HRC}} \right] \tag{7}$$

## 4. Results and discussion

### 4.1. Conventional I&S plant results

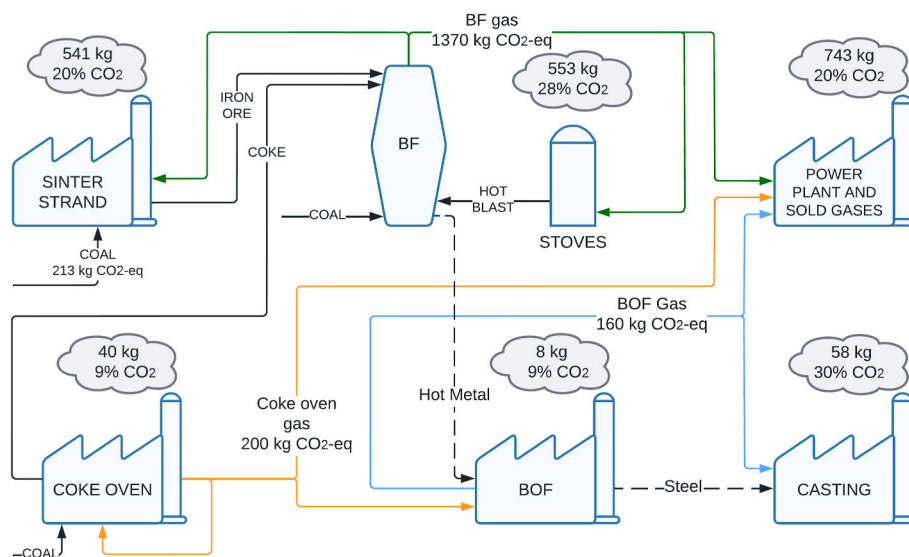
The conventional I&S plant model was validated with literature data. Assuming a 320 t<sub>HM</sub>/h production plant, the main consumptions are 1464 kg/t<sub>HM</sub> of iron ore, 668 kg/t<sub>HM</sub> of coal, and 150 kg/t<sub>HM</sub> of scrap. The coal is derived to the coke oven for coke production (443 kg/t<sub>HM</sub>), the sintering (75 kg/t<sub>HM</sub>) and the blast furnace as PCI (150 kg/t<sub>HM</sub>). The AFT in the BF is 2258 °C and the energetic gases sold to other industries account for 2400 MJ/t<sub>HM</sub>.

The CO<sub>2</sub> emissions and their concentration in flue gases for the conventional steel plant simulated in Aspen are shown in Fig. 4. The total CO<sub>2</sub> emissions are 1943 kgCO<sub>2</sub>/t<sub>HM</sub>, and the most contaminant stream is the BFG, with 1370 kgCO<sub>2</sub>-eq/t<sub>HM</sub> in form of CO and CO<sub>2</sub>. Table 2 shows the main mass flow streams for the conventional I&S plant simulated in Aspen, where all results agree with bibliography data, validating the conventional I&S plant model. More details about stream results and validation data can be found in (Perpiñán et al., 2022a,b).

### 4.2. PtG-steelmaking integration: Blast furnace results

The amount of reducing agents injected in the BF (coke, PCI and SNG), as well as the total CO<sub>2</sub> emissions from the I&S plant, are analysed as a function of the oxygen enrichment and its temperature in Fig. 5. With low oxygen injection, there is a drastic increase in SNG injection, being more pronounced when injecting O<sub>2</sub> at 1200 °C. With higher oxygen enrichments, the same benefits are found but less pronounced, achieving a maximum injection of 192 kgSNG/t<sub>HM</sub> for O<sub>2</sub> at 1200 °C. This result agrees with that obtained by Pistorius et al. (Sato et al., 2015), who simulated injections of 180 kgSNG/t<sub>HM</sub>, with an oxygen enrichment of 39%. At this point, all PCI has been substituted along with 53.5 kg/t<sub>HM</sub> of coke. When injecting 40% O<sub>2</sub> at 1200 °C, the PCI is completely substituted, but when injecting oxygen at 25 °C, the PCI is never fully substituted. For all cases analysed, the AFT is set to 2000 °C.

For the case of 95% of hot oxygen enrichment, the coke consumption is 278.5 kg/t<sub>HM</sub>, with no PCI injection. In order to put these results into perspective, Sahu et al. (2015) investigated the impact of the nature of the fuel and burden of the OBF process with top gas recycling, obtaining 323–342 kg<sub>coke</sub>/t<sub>HM</sub> and 200 kg<sub>PCI</sub>/t<sub>HM</sub>. Zhang et al. (2017) studied the

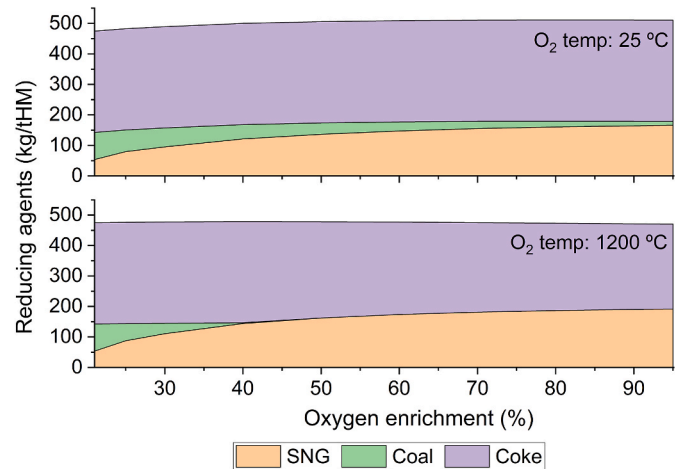


**Fig. 4.** Distribution of energetic gases for the conventional I&S plant: BF gas green line, Coke oven gas orange line, BOF gas blue line; and energetic content of each energetic gas in MJ/t<sub>HM</sub>. CO<sub>2</sub> emissions, expressed in volume (kg/t<sub>HM</sub>) and concentration in flue gas (volume %) are also shown in the Aspen model. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 2**

Mass flows (kg/t<sub>HM</sub>) of the main streams for the conventional I&S plant simulated in Aspen compared to typical values from (A. Babich, D. Senk, H. W. Gudenau, 2008; He and Wang, 2017).

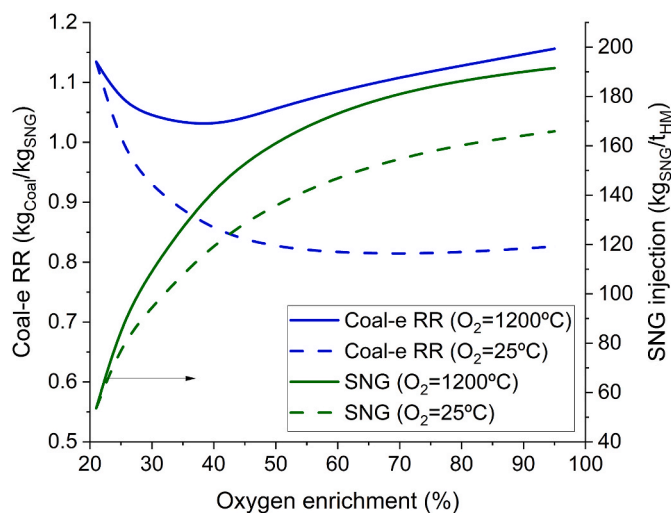
Material	Typical values	Present model
Iron ore	1315–1510	1464
Coal (Sinter)	45–75	75
Coal (Coke Oven)	380–534	443
Coal (BF)	150–200	150
Coke	300–400	332
COG	100–140	111
Hot blast	1100–1600	1449
BFG	1800–2420	2216
BF Slag	260–298	261
Pig iron	900–1000	1000
Scrap (BOF)	150	150
O <sub>2</sub> (BOF)	60–90	87
BOFG	90–130	128
Final Steel	1000–1100	1079



**Fig. 5.** Reducing agents in BF (orange area: SNG; green area: coal; purple area: coke) as a function of the oxygen temperature and its percentage in the hot blast. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

medium (50% O<sub>2</sub>) and full (98% O<sub>2</sub>) oxygen enriched blast furnace with top gas recycling, reaching a consumption of 300 kg<sub>coke</sub>/t<sub>HM</sub> and 126 kg<sub>PCI</sub>/t<sub>HM</sub> for medium OBF and 200 kg<sub>coke</sub>/t<sub>HM</sub> and 205 kg<sub>PCI</sub>/t<sub>HM</sub> for full OBF. A similar study with similar results was performed by Li et al. (C. L. Li et al., 2019), with 337 kg<sub>coke</sub>/t<sub>HM</sub> and 150 kg<sub>PCI</sub>/t<sub>HM</sub> for medium OBF and 200 kg<sub>coke</sub>/t<sub>HM</sub> and 205 kg<sub>PCI</sub>/t<sub>HM</sub> for full OBF. However, further studies that use data-driven analyses with actual long term plant data are required (Zhai and Chen, 2023).

The coal-e RR and the SNG injection are shown in Fig. 6. The coal-e RR is among 1.05–1.15 kg<sub>Coal</sub>/kg<sub>SNG</sub> when O<sub>2</sub> is preheated at 1200 °C, with a slight decrease at low oxygen enrichment. It can get as low as 0.81 kg<sub>Coal</sub>/kg<sub>SNG</sub> if cold oxygen is injected. This difference is because cold oxygen lowers the AFT and therefore less SNG can be injected and less PCI can be substituted. Dashed lines in Fig. 6 and following figures mean



**Fig. 6.** Coal equivalent replacement ratio (Coal-e RR, blue lines) and SNG injection (green lines) as a function of the oxygen temperature (1200 °C in solid lines and 25 °C in dashed lines) and its percentage in the hot blast. Where SNG is the synthetic natural gas injected in the BF tuyeres and Coal-e RR is the sum of the pulverised coal injection and the coking coal replaced by the SNG. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

low temperature (25 °C) oxygen enrichment.

When increasing the oxygen enrichment in the hot blast, more SNG can be injected, hence less N<sub>2</sub> and more CO<sub>2</sub>, CO and H<sub>2</sub> can be found in the BFG, see Fig. 7. Moreover, these percentages are not significantly dependent on temperature. When 95% O<sub>2</sub> is used, H<sub>2</sub> percentage contents of 23–28% are found, in agreement with Sato et al. (2015) who simulate an OBF with high NG injection, reaching 25% H<sub>2</sub> in BFG). The increasing contribution of CO and H<sub>2</sub> promotes a higher BFG LHV (MJ/kg<sub>BFG</sub>), but the decreasing contribution of N<sub>2</sub> promotes a lower BFG mass flow rate (kg<sub>BFG</sub>/t<sub>HM</sub>). Fig. 7 joins the two parameters showing the BFG energy content (MJ/t<sub>HM</sub>), which can achieve 8086 MJ/t<sub>HM</sub>, compared with the 4930 MJ/t<sub>HM</sub> obtained in the conventional I&S plant. This value is in accordance with the literature, specifically Pistorius et al. (2017) inject similar amounts of NG resulting in 7000–8000 MJ/t<sub>HM</sub>.

Fig. 8 shows the amount of preheating gas injection needed to keep the BFG temperature above 150 °C, and the CO utilization (μ<sub>CO</sub>) in the BF, as a function of the oxygen enrichment and its temperature. The BFG temperature decreases clearly when increasing the O<sub>2</sub> percentage in the hot blast and when injecting high amounts of SNG, as explained before. Thus, preheating gas injection is needed when the oxygen enrichment is above 30%, achieving a maximum value of 233 kg<sub>BFG</sub>/t<sub>HM</sub>, which agrees with Sato et al. (2015) who simulates an OBF with high NG injection, injecting 213 kg<sub>BFG</sub>/t<sub>HM</sub> as preheating gas. The CO utilization exhibits a minimum at 30% oxygen enrichment, but then increases with the preheating gas injection, being in a range of 42–52%. This is mainly because of the large CO<sub>2</sub> content of the injected preheated gas (which ends up in the BFG), and the definition of Eq. (1) for the CO utilization, which was referred to the final BFG composition.

### 4.3. PtG-steelmaking heat integration and energy penalty

Table 3 shows the molar composition and the lower heating value (LHV) of the main gaseous streams for both the conventional I&S plant and the PtG-steelmaking integration. Note that BFG, clean-BFG and sold gases have a wide range of data which depend on the O<sub>2</sub> enrichment of the hot blast, as it lowers the N<sub>2</sub> content in the BFG. Considering all compositions and impurities in Table 3, the total CO<sub>2</sub> and H<sub>2</sub> streams needed in the methanation plant are 2.7 kg<sub>CO2</sub>/kg<sub>SNG</sub> and 0.49 kg<sub>H2</sub>/kg<sub>SNG</sub>, respectively.

The heat consumption in amine scrubbing can be covered by the exothermic heat of the methanation. A pinch analysis validating this

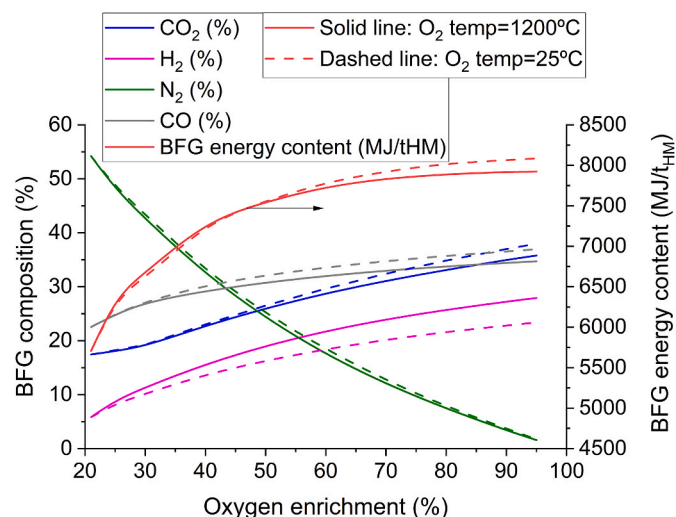


Fig. 7. BFG composition (blue lines: CO<sub>2</sub>; pink lines: H<sub>2</sub>; green lines: N<sub>2</sub>; grey lines: CO) and BFG energy content (red lines) as a function of the oxygen temperature (1200 °C in solid lines and 25 °C in dashed lines) and its percentage in the hot blast. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

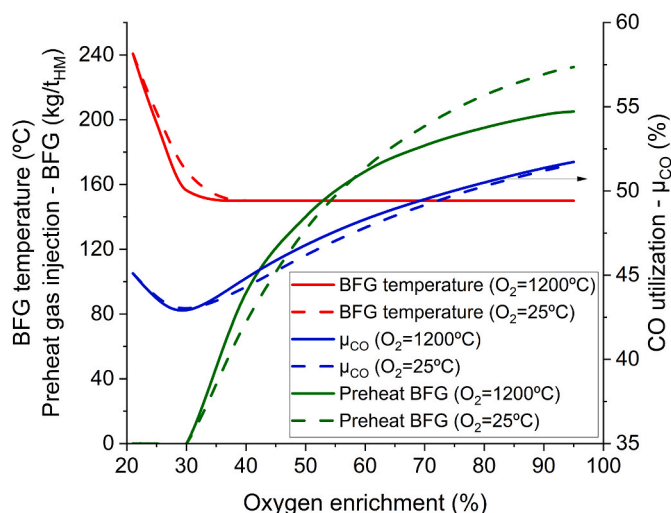


Fig. 8. BFG temperature (red lines), preheating gas injection (green lines) and CO utilization (μ<sub>CO</sub>, blue lines) as a function of the oxygen temperature (1200 °C in solid lines and 25 °C in dashed lines) and its percentage in the hot blast. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

amine-methanation heat integration was undertaken via Pinch analysis using Aspen Energy Analyzer tool when using atmospheric air (i.e., no oxygen enrichment in the hot blast). The methanation temperature ranges between 300 and 350 °C, while the amine scrubbing is between 110 and 130 °C. A minimum of five different heat exchangers are needed to fulfil the thermal needs. More details about the pinch analysis when using atmospheric air can be found in (Perpiñán et al., 2022a,b).

When increasing the oxygen enrichment in the hot blast, the CO<sub>2</sub> content in the BFG increases, which implies a lower amine specific heat consumption (see Fig. 9). As the exothermic methanation heat remains constant (per kilogram of captured CO<sub>2</sub>), it can be asserted that the amine heat demand can be covered by the methanation in all cases. This means that the amine heat consumption decreases from 3.7 to 3.1 MJ/kg<sub>CO2</sub>, while the heat released by the methanation is always 6.1 MJ/kg<sub>CO2</sub>.

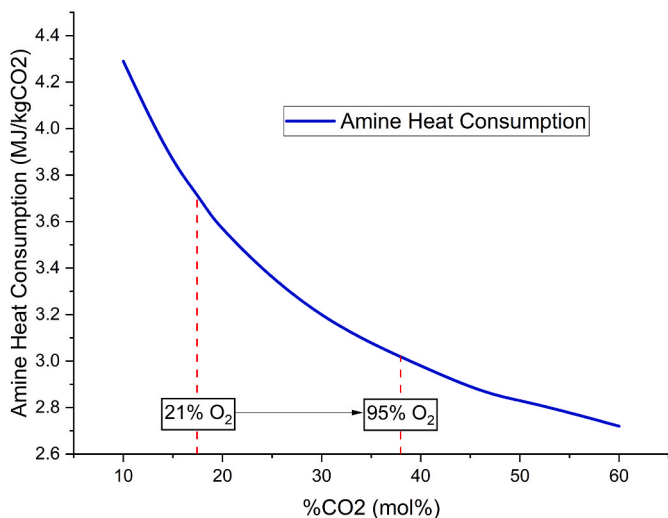
The PEM size increases with the O<sub>2</sub> enrichment and its temperature (see Fig. 10). Higher O<sub>2</sub> enrichments and temperatures allow for higher SNG injections, which require higher H<sub>2</sub> production and therefore higher PEM sizes. The PEM size ranges from 355 MW when injecting air, to 1268 MW when injecting 95% O<sub>2</sub> at 1200 °C. The O<sub>2</sub> by-produced (red lines) grows proportionally up to 739 kg/t<sub>HM</sub>, which is always above the O<sub>2</sub> consumed in the hot blast and the BOF (blue lines). It is important to highlight that for the same oxygen enrichment; more oxygen is needed when injecting cold oxygen. This is because, at lower oxygen temperatures, less coal can be substituted (see coal-e RR, Fig. 6), and therefore there is a greater amount of reducing agents in the BF (see Fig. 5), requiring more oxygen to burn them.

Fig. 11 shows the main streams with their CO<sub>2</sub>-eq content, i.e., the CO<sub>2</sub> generated after burning the carbonaceous components (C, CO and CH<sub>4</sub>), as well as the total CO<sub>2</sub> emissions for the PtG-steelmaking integration. Total CO<sub>2</sub> emissions can be calculated in three different ways (Eq. (8)): by adding the flue gases CO<sub>2</sub> emissions; by adding the CO<sub>2</sub>-eq emissions from the input coal streams; or by adding the sintering coal, the intermediate gaseous streams (BFG, BOFG and COG) and the recirculated streams (SNG and preheating gas) CO<sub>2</sub>-eq emissions.

The BOFG and the sintering coal CO<sub>2</sub>-eq content are constant because the current integration does not influence these processes. The COG CO<sub>2</sub>-eq content decreases slightly for the hot oxygen (1200 °C) integration, as part of the coking coal is replaced, but is constant in the cold oxygen (25 °C) integration. The BFG CO<sub>2</sub>-eq content increases due to the high amount of SNG and preheating gas injected into the furnace.

**Table 3**  
Molar composition and lower heating value for gas streams in both the conventional process plant and proposed plant with PtG and amine scrubbing.

	Composition (vol %)	O <sub>2</sub>	N <sub>2</sub>	CO	CO <sub>2</sub>	H <sub>2</sub>	H <sub>2</sub> O	CH <sub>4</sub>	Ar	LHV (MJ/kg)
Conventional I&S	COG	0.07	2.26	9.37	2.34	57.31	–	28.65	–	39.27
	BOFG	1.93	8.00	66.00	19.35	2.00	–	–	2.72	6.18
	BFG	–	55.10	21.98	19.37	2.25	1.3	–	–	2.23
	O <sub>2</sub>	95.00	0.8	–	–	–	–	–	4.2	–
PtG-steelmaking integration	Sold gases	0.15	39.95	22.10	15.51	14.70	0.92	6.49	0.18	5.81
	COG	0.07	2.26	9.37	2.34	57.31	–	28.65	–	39.27
	BOFG	3.31	8.00	66.00	20.69	2.00	–	–	–	6.18
	BFG	–	1.57–55.1	21.23–35.65	17.44–37.97	2.25–27.92	1.3–1.3	–	–	2.23–6.15
	Clean BFG	–	2.32–66.73	24.82–54.23	2.07–5.77	2.73–41.19	1.9–1.9	–	–	3.29–13.34
	O <sub>2</sub>	99.98	–	–	–	0.02	–	–	–	–
	H <sub>2</sub>	–	–	–	–	100.0	–	–	–	119.9
	CO <sub>2</sub>	–	0.02	0.79	95.82	–	3.36	–	–	–
	SNG	–	0.02	–	0.96	3.86	4.96	94.65	–	48.73
	Sold gases	0.23–0.35	2.7–44.94	23.41–42.36	7.51–10.33	17.51–39.44	1.00–1.46	4.81–6.41	–	6.69–13.47



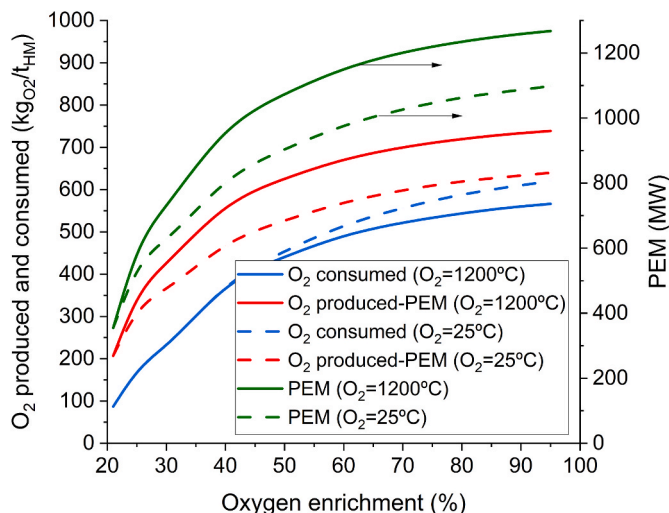
**Fig. 9.** Amine heat consumption as a function of the CO<sub>2</sub> percentage in the BFG. Red dashed lines represent the 21% oxygen content and the 95% oxygen content in the hot blast. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The SNG and the preheating gas have negative values, as this CO<sub>2</sub>-eq flow rate is not emitted into the atmosphere but recycled and constantly recirculated in the system. Regarding total CO<sub>2</sub> emissions, a linear dependency with the SNG injection is obtained. When injecting pure oxygen at 25 °C, 22% of CO<sub>2</sub> saving is achieved, but when preheating the oxygen to 1200 °C, 34% CO<sub>2</sub> savings are achieved, with respect to the conventional I&S plant.

$$\begin{aligned}
 \text{Total CO}_2 \text{ emissions} &= \Sigma \text{ Flue gases} = \text{Sint.Coal} + \text{Coking Coal} + \text{PCI} \\
 &= \text{Sint.Coal} + \text{BFG} + \text{BOFG} + \text{COG} \\
 &\quad - \text{SNG} - \text{Preheating gas}
 \end{aligned}
 \tag{8}$$

The sold gases, electricity consumption and energy penalty are represented in Fig. 12. The sold gases (BFG, BOFG and COG) increase at first and then stabilize at 4500–5500 MJ/t<sub>HM</sub>, being double than that obtained in the conventional I&S plant (2400 MJ/t<sub>HM</sub>). This is caused by the increasing energy content of the BFG (see Fig. 7) counteracted by the BFG consumed in the preheating gas, 0–1313 MJ/t<sub>HM</sub> (see Fig. 8), and in the SNG heating, 111–271 MJ/t<sub>HM</sub>.

The electricity consumption has a direct correlation with the PEM size, and therefore with the SNG injected in the BFG, since other electricity consumptions barely vary. The total electricity consumption rises from 5000 MJ/t<sub>HM</sub> when injecting air, to 15,600 MJ/t<sub>HM</sub> when injecting



**Fig. 10.** Oxygen produced in the PEM (red lines), oxygen consumed in the industry (blue lines) and PEM capacity (green lines) as a function of the oxygen temperature (1200 °C in solid lines and 25 °C in dashed lines) and its percentage in the hot blast. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

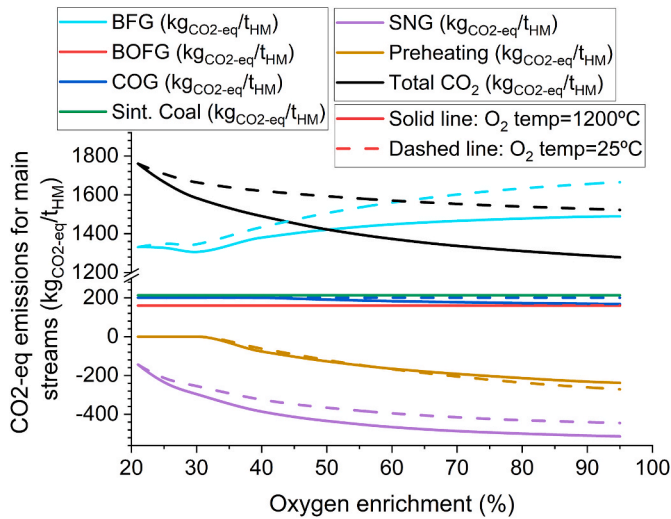
95% O<sub>2</sub> at 1200 °C, compared to the 950 MJ/t<sub>HM</sub> obtained in the conventional I&S plant. The electricity production in the power plant has been kept constant at 1122 MJ/t<sub>HM</sub> (100 MW). Other minor electrical consumptions added are the pumps in the amine system and the CO<sub>2</sub> and H<sub>2</sub> compressors prior to methanation, accounting for 9–15 MJ/t<sub>HM</sub> and 231–400 MJ/t<sub>HM</sub> respectively. The energy penalty shows a great difference when using cold oxygen (21–25 MJ/kgCO<sub>2</sub>) or hot oxygen (17–19 MJ/kgCO<sub>2</sub>), being 16 MJ/kgCO<sub>2</sub> when using atmospheric air.

#### 4.4. Economic analysis

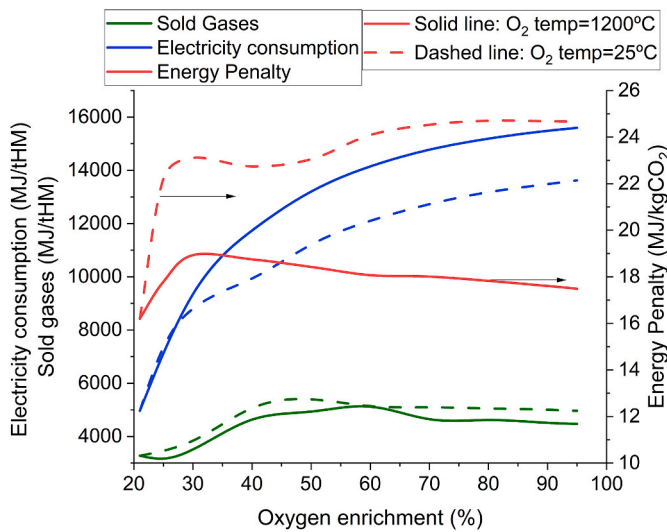
When increasing the oxygen enrichment in the hot blast, the Capex and Opex increase, due to higher carbon capture and electrolysis plants, and higher electricity consumption (Table 4). Capex and Opex have values between 268 and 1157 M€ and 221–835 M€/year, respectively. The PEM electrolyser accounts for 44–53% of the Capex, and the renewable purchased electricity accounts for 94–96% of the Opex. However, when increasing the oxygen enrichment, the Incomes also increase, mainly due to higher coal saved and CO<sub>2</sub> taxes saved, ranging between 102 and 294 M€/year. The CO<sub>2</sub> taxes saved accounts for 39–49% of the Incomes.

The specific carbon capture (CC) cost, in €/tCO<sub>2</sub> and €/tHRC, is shown in Fig. 13 as a function of the oxygen enrichment and its temperature.





**Fig. 11.** CO<sub>2</sub> equivalent (CO<sub>2</sub>-eq) emissions for the main streams: BFG in the blue line, BOFG in the red line, COG in the dark blue line, sinter coal in the green line, SNG in the purple line, preheating gas in the yellow line and total CO<sub>2</sub> emissions in black line; as a function of the oxygen temperature (1200 °C in solid lines and 25 °C in dashed lines) and its percentage in the hot blast. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



**Fig. 12.** Electricity consumption (blue line), sold gases (green line) and energy penalty (red line) as a function of the oxygen temperature (1200 °C for the solid line and 25 °C for the dashed line) and its percentage in the hot blast. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

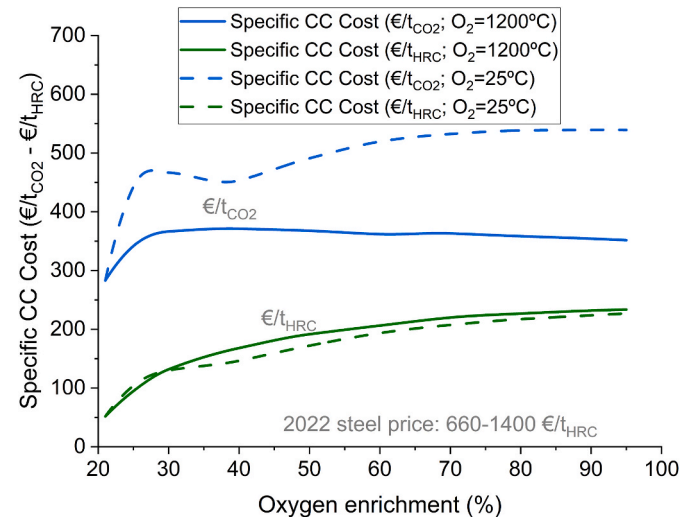
Since the steel price is around 660–1400 €/t<sub>HRC</sub> in 2022 (*Marketwatch Web Page (HRC Steel)*, 2022), the specific CC cost –in €/t<sub>HRC</sub>– represents 4–35% of the actual steel price, depending on the oxygen enrichment degree. Contrary to this variable, the specific CC cost regarding the CO<sub>2</sub> avoided (€/t<sub>CO<sub>2</sub></sub>) is highly dependent on the oxygen temperature, due to the lower CO<sub>2</sub> abatement when injecting cold oxygen. For illustration purposes, 30–95% of hot oxygen enrichment may be compared: the CO<sub>2</sub> abatement is 19–34% with a cost of 366–352 €/t<sub>CO<sub>2</sub></sub>, respectively; whereas for cold oxygen enrichment the CO<sub>2</sub> abatement is 14–22% with a cost of 466–539 €/t<sub>CO<sub>2</sub></sub>, respectively (see *Figs. 5 and 13*).

Regarding discounted pay-back period, two representative situations have been investigated: 21% O<sub>2</sub> in the hot blast (corresponding with a PEM size of 355 MW) and 95% O<sub>2</sub> at 1200 °C (corresponding to a PEM

**Table 4**

Main results for the economic analysis of the PtG integration in the iron and steel industry, for the data points of 21% O<sub>2</sub>, 95% O<sub>2</sub> at 25 °C and 95% O<sub>2</sub> at 1200 °C.

	21% O <sub>2</sub>	95% O <sub>2</sub> at 25 °C	95% O <sub>2</sub> at 1200 °C
<b>CAPEX [M€]</b>	<b>267.8</b>	<b>1027.4</b>	<b>1156.7</b>
Amine Plant			
Overall Cost	7.39	12.71	17.11
Electrolysis			
Overall Cost	141.92	439.26	507.04
Methanation			
H <sub>2</sub> compressor	0.036	0.077	0.084
CO <sub>2</sub> compressor	0.017	0.037	0.041
Reactors	0.245	0.760	0.877
Catalyst	4.39	13.59	15.68
Heat exchangers			
BF retrofitting	0.429	1.047	1.173
Other direct costs			
Installation	15.44	59.25	66.70
Instrumentation & control	6.18	23.70	26.68
Piping	24.71	94.80	106.72
Electrical	7.72	29.62	33.35
Building	7.72	29.62	33.35
Land	1.54	5.92	6.67
Indirect costs			
Engineering	15.24	58.48	65.83
Legal expenses	5.36	20.55	23.13
Construction expenses	10.71	41.10	46.27
Contingency	18.75	71.92	80.97
<b>OPEX [M€/year]</b>	<b>220.69</b>	<b>722.14</b>	<b>835.38</b>
Amine renovation	0.16	0.36	0.57
Catalyst renovation	0.66	2.04	2.35
Electricity	210.97	686.22	794.64
Water	0.87	2.69	3.11
O&M	8.03	30.82	34.70
<b>INCOMES [M€/year]</b>	<b>101.69</b>	<b>191.43</b>	<b>293.94</b>
Coal	20.36	45.88	74.12
Oxygen	24.59	4.15	35.42
CO <sub>2</sub> taxes	39.46	90.98	143.66
Steel gases	17.28	50.42	40.74



**Fig. 13.** Specific carbon capture (CC) cost in €/t<sub>CO<sub>2</sub></sub> and €/t<sub>HRC</sub> as a function of the oxygen temperature (1200 °C for the solid line and 25 °C for the dashed line) and its percentage in the hot blast (2022 steel price (*Marketwatch Web Page (HRC Steel)*, 2022)).

size of 1268 MW), both with a BF size of 320 t<sub>HM</sub>/h, see *Fig. 14*. They correspond to the maximum CO<sub>2</sub> reduction and maximum profitability cases, respectively. The rest of cases are intermediate cases. The parametric analyses look for the most favourable combinations of CO<sub>2</sub> allowances and electricity prices that make the Power to Gas integration

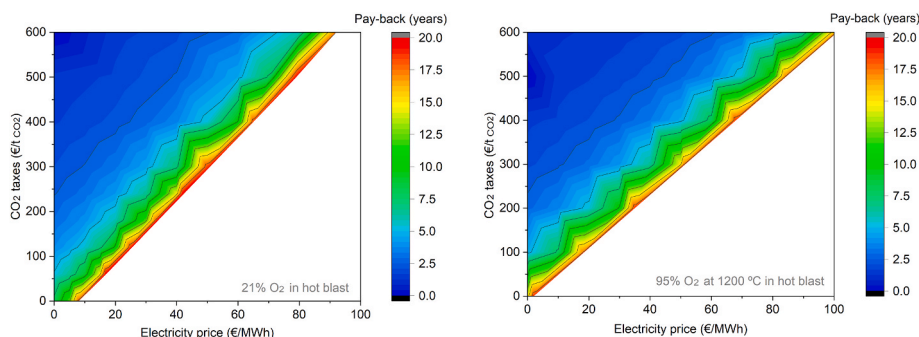


Fig. 14. Pay-back in years as a function of the CO<sub>2</sub> taxes and the electricity price, for the data points of 21% O<sub>2</sub> in the hot blast (left) and 95% O<sub>2</sub> at 1200 °C (right).

economically viable. A maximum of 20 years has been fixed as it is the replacement period of some important equipment as the blast furnace. This economic study indicates that profitable scenarios would require the supply of electricity at the cost of production or subsidies given to the industry.

It is important to highlight the exponential descent of the pay-back, as values higher than 13 years (red area) are in a very reduced area, values between 6 and 13 years (green area) are in a small area, and values lower than 6 years (blue area) cover most of the profitable price-tax mix. This means that for a given value of electricity price, e.g. 35 €/MWh (cost of production for wind power (IRENA, 2022)), the pay-back is 20 years when the CO<sub>2</sub> tax is 135 €/tCO<sub>2</sub> for the first data point and 200 €/tCO<sub>2</sub> for the second one; but the payback changes to 6 years when the CO<sub>2</sub> tax is 200 €/tCO<sub>2</sub> and 300 €/tCO<sub>2</sub>, respectively.

## 5. Conclusions

A novel concept of integration of Power to Gas (PtG) technology in the steelmaking industry with oxygen enrichment of the hot blast was presented in this study. Renewable electricity is used to power a PEM electrolyser that produces green H<sub>2</sub>, an MDEA amine plant captures CO<sub>2</sub> from the BFG, and a methanation reactor produces synthetic natural gas (SNG) from the two previous components. This SNG is injected into the blast furnace (BF), thus recycling CO<sub>2</sub> in a closed loop and reducing coal consumption. Along with this PtG integration, the oxygen enrichment has been studied at two different temperatures, 25 °C and 1200 °C, and its percentage in the hot blast ranges from 21% (atmospheric air) to 95%.

For all the parameters analysed, better results were found with hot oxygen (1200 °C) compared to that at ambient temperature (25 °C). Similarly, the oxygen enrichment analysis showed better technical results at higher oxygen percentages, but also higher costs, compared to that with low oxygen enrichment. Therefore, when injecting 95% O<sub>2</sub> at 1200 °C in the hot blast, 192 kg<sub>SNG</sub>/t<sub>HM</sub> can be injected, substituting all the pulverised coal injection (PCI) and 16% of the coke, causing an overall CO<sub>2</sub> emission reduction of 34% (equivalent to 664 kg<sub>CO2</sub>/t<sub>HM</sub>). The overall coal reduction accounts for 221 kg/t<sub>HM</sub> (33% of current coal consumption).

The BFG increases its energy content from 4930 MJ/t<sub>HM</sub> when atmospheric air to 8086 MJ/t<sub>HM</sub> when 95% O<sub>2</sub>, due to the reduced N<sub>2</sub> contribution and the high SNG injection that increases the H<sub>2</sub> contribution. Due to the increase in the BFG energy content, the energy needs for the downstream processes are covered, avoiding a problem that usually appears in TGR configurations. The BFG temperature decreases sharply when injecting oxygen, which makes necessary a preheating gas injection in the upper part of the shaft when the oxygen enrichment is above 30%.

The thermal integration between the amine heat consumption and the exothermic heat of the methanation has demonstrated that no extra energy is needed to cover the amine thermal demand. The PEM electrolyser is sized between 355 MW and 1268 MW depending on the

oxygen enrichment and its temperature. The oxygen by-produced in the electrolyser is used to eliminate the ASU and to feed the BOF and hot blast enrichment necessities. The overall electricity consumption increases between 5 and 16 times compared to the conventional I&S plant, accounting the PEM for 92% of the total electricity consumption.

The energy penalty obtained is dependent on the oxygen temperature, likewise if using cold oxygen 25 MJ/kg<sub>CO2</sub> is achieved, but if using hot oxygen (1200 °C) 17 MJ/kg<sub>CO2</sub> is achieved. Under the current economic situation, the specific carbon capture (CC) cost is between 4 and 35% of the actual steel price. Economic profitability can be achieved with certain combinations of electricity price, CO<sub>2</sub> tax or economic subsidies.

The main economic limitation of this study is the uncertainty in future carbon and electricity prices, as these variables have a great influence on the specific carbon capture costs. Regarding the technical limitations, the feasibility of an OBF can be seen as the main concern, since these types of furnaces are still under development and have not yet reached the commercial stage. Additionally, each I&S industry has its unique equipment layouts, which can impact the practical implementation of this concept.

In general, this novel concept of PtG technology in the steelmaking industry with oxygen enrichment has the advantage of reducing fuel consumption and CO<sub>2</sub> emissions, while avoiding geological storage as the carbon is recycled. This PtG configuration consumes renewable electricity, producing green hydrogen and later SNG. More PtG integration concepts in the blast furnace ironmaking will be considered in future work to reduce energy penalties and costs.

## CRediT authorship contribution statement

**Jorge Perpiñán:** Conceptualization, Methodology, model, Formal analysis, Writing – original draft, Visualization. **Manuel Bailera:** Conceptualization, Methodology, model, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Begona Peña:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Luis M. Romeo:** Writing – review & editing, Project administration, Funding acquisition. All authors have read and agreed to the published version of the manuscript. **Valerie Evelyoy:** Writing – review & editing, Project administration, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2023.137001>.

## References

- Abdul Quader, M., Ahmed, S., Dawal, S.Z., Nukman, Y., 2016. Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO<sub>2</sub>) Steelmaking (ULCOS) program. *Renew. Sustain. Energy Rev.* 55, 537–549. <https://doi.org/10.1016/j.rser.2015.10.101>.
- Abu-Zahra, M.R.M., Niederer, J.P.M., Feron, P.H.M., Versteeg, G.F., 2007. CO<sub>2</sub> capture from power plants. Part II. A parametric study of the economical performance based on mono-ethanolamine. *Int. J. Greenh. Gas Control* 1 (2), 135–142. [https://doi.org/10.1016/S1750-5836\(07\)00032-1](https://doi.org/10.1016/S1750-5836(07)00032-1).
- Andrade de Castro, L.F., Tavares, R.P., Seshadri, V., 2005. Process control model for charcoal blast furnaces in Brazil. *Mater. Manuf. Process.* 20 (2), 287–298. <https://doi.org/10.1081/amp-200042085>.
- ArceLorMittal, 2023. Technology Pathways to Net-Zero Steel. <https://corporate.arcelormittal.com/climate-action/technology-pathways-to-net-zero-steel>.
- Ariyama, T., Sato, M., Nouchi, T., Takahashi, K., 2016. Evolution of blast furnace process toward reductant flexibility and carbon dioxide mitigation in steel works. *ISIJ Int.* 56 (10), 1681–1696. <https://doi.org/10.2355/isijinternational.ISIJINT-2016-210>.
- Aspen Technology Inc, 2019a. Aspen Energy Analyzer. AspenTech.
- Aspen Technology Inc, 2019b. Aspen Examples - Reference Manual. AspenTech.
- Aspen Technology Inc, 2019c. Aspen Physical Property Methods - Reference Manual. AspenTech.
- Babich, A., Senk, D., Gudenau, H.W., K. T. M., 2008. IRONMAKING, p. 402.
- Bailera, M., Espatolero, S., Lisbona, P., Romeo, L.M., 2017a. Power to gas-electrochemical industry hybrid systems: a case study. *Appl. Energy* 202, 435–446. <https://doi.org/10.1016/j.apenergy.2017.05.177>, 2017.
- Bailera, M., Lisbona, P., Romeo, L.M., Espatolero, S., 2017b. Power to Gas projects review: lab, pilot and demo plants for storing renewable energy and CO<sub>2</sub>. *Renew. Sustain. Energy Rev.* 69 (November 2016), 292–312. <https://doi.org/10.1016/j.rser.2016.11.130>.
- Bailera, M., Lisbona, P., Pena, B., Romeo, L.M., 2021a. A review on CO<sub>2</sub> mitigation in the Iron and Steel industry through Power to X processes. *J. CO<sub>2</sub> Util.* 46 (November 2020), 101456. <https://doi.org/10.1016/j.jcou.2021.101456>.
- Bailera, M., Nakagaki, T., Kataoka, R., 2021b. Revisiting the Rist Diagram for Predicting Operating Conditions in Blast Furnaces with Multiple Injections. <https://doi.org/10.12688/openreseurope.14275.1>.
- Bailera, M., Lisbona, P., Pena, B., Alarcon, A., Guilera, J., Perpinan, J., Romeo, L.M., 2022a. Synthetic natural gas production in a 1 kW reactor using Ni-Ce/Al<sub>2</sub>O<sub>3</sub> and Ru-Ce/Al<sub>2</sub>O<sub>3</sub>: kinetics, catalyst degradation and process design. *Energy* 256. <https://doi.org/10.1016/j.energy.2022.124720>.
- Bailera, M., Nakagaki, T., Kataoka, R., 2022b. Limits on the integration of power to gas with blast furnace ironmaking. *J. Clean. Prod.*, 134038. <https://doi.org/10.1016/j.jclepro.2022.134038>.
- Benjaminsson, G., Benjaminsson, J., Rudberg, R.B., 2013. Power-to-Gas - A Technical Review. [http://sgc.camerose.se/ckfinder/userfiles/files/SGC284\\_eng.pdf](http://sgc.camerose.se/ckfinder/userfiles/files/SGC284_eng.pdf).
- De Saint Jean, M., Baurens, P., Bouallou, C., Couturier, K., 2015. Economic assessment of a power-to-substitute-natural-gas process including high-temperature steam electrolysis. *Int. J. Hydrogen Energy* 40 (20), 6487–6500. <https://doi.org/10.1016/j.ijhydene.2015.03.066>.
- European Commission, 2022. [https://energy.ec.europa.eu/index\\_es](https://energy.ec.europa.eu/index_es).
- He, K., Wang, L., 2017. A review of energy use and energy-efficient technologies for the iron and steel industry. *Renew. Sustain. Energy Rev.* 70 (September 2016), 1022–1039. <https://doi.org/10.1016/j.rser.2016.12.007>.
- Hisashige, S., Nakagaki, T., Yamamoto, T., 2019. CO<sub>2</sub> emission reduction and exergy analysis of smart steelmaking system adaptive for flexible operating conditions. *ISIJ Int.* 59 (4), 598–606. <https://doi.org/10.2355/isijinternational.ISIJINT-2018-355>.
- Hurskainen, M., 2017. Industrial Oxygen Demand in Finland. <https://www.vttresearch.com/sites/default/files/julkaisut/muut/2017/VTT-R-06563-17.pdf>.
- IEA - iron & steel roadmap. <https://www.iea.org/reports/iron-and-steel-technology-roadmap>, 2020.
- Intergovernmental, 2022. Panel on climate change (IPCC). <https://www.ipcc.ch/>.
- International Energy Agency, 2020. Iron and steel technology roadmap. <https://www.iea.org/reports/iron-and-steel-technology-roadmap>.
- IRENA, 2022. <https://www.irena.org/costs/Power-Generation-Costs>.
- Izumiya, K., Shimada, I., 2021. K<sub>2</sub>-Methane Producing Technology from CO<sub>2</sub> for Carbon Recycling, pp. 34–35.
- Kim, H., Kang, T., Kaiser, K., Liedel, S., Jarry, L., Paubel, X., Jumani, Y., Kaya, L., 2016. Heat Oxy-Combustion: An Innovative Energy Saving Solution For Glass Industry. 76th Conference on Glass Problems Edited by S. K. Sundaram 1, 185–191.
- Kohl, A.L., Nielsen, R.B., 1997. Gas purification. <https://doi.org/10.1016/B978-0-88415-220-0.X5000-9>.
- Lehner, M., Tichler, R., Steinmuller, H., Koppe, M., 2014. Power-to-Gas: technology and business models. <https://link.springer.com/book/10.1007/978-3-319-03995-4?noAccess=true>.
- Li, C.L., Xue, Q.G., Liu, Y.L., Dong, Z.S., Wang, G., Wang, J.S., 2019. Comprehensive analysis on material and exergy balances of oxygen blast furnace. *Ironmak. Steelmak.* 46 (8), 761–770. <https://doi.org/10.1080/03019233.2017.1410947>.
- Li, R., Lian, S., Zhang, Z., Song, C., Han, R., Liu, Q., 2022. Techno-economic evaluation of a novel membrane-cryogenic hybrid process for carbon capture. *Appl. Therm. Eng.* 200. <https://doi.org/10.1016/j.applthermaleng.2021.117688>.
- Mac Dowell, N., Fennell, P.S., Shah, N., Maitland, G.C., 2017. The role of CO<sub>2</sub> capture and utilization in mitigating climate change. *Nat. Clim. Change* 7 (4), 243–249. <https://doi.org/10.1038/nclimate3231>.
- Marketwatch Web Page (HRC Steel), 2022. <https://www.marketwatch.com/investing/index/steel?countryCode=XX>.
- Nie, H., Li, Z., Kuang, S., Yan, L., Zhong, W., Yu, A., Mao, X., Xu, H., 2021. Numerical investigation of oxygen-enriched operations in blast furnace ironmaking. *Fuel* 296. <https://doi.org/10.1016/j.fuel.2021.120662>, July 2020.
- Peacey, J.G., Davbenport, W.G., 1979. *The Iron Blast Furnace. Theory and Practice*, 1979.
- Perpiñán, J., Bailera, M., Romeo, L.M., Pena, B., Eveloy, V., 2021. CO<sub>2</sub> recycling in the iron and steel industry via power-to-gas and oxy-fuel combustion. *Energies* 14 (21), 7090. <https://doi.org/10.3390/en14217090>.
- Perpinan, J., Bailera, M., Pena, B., Romeo, L.M., Eveloy, V., 2022a. Technical and economic assessment of iron and steelmaking decarbonisation via power to gas and amine scrubbing. *ReVision*.
- Perpiñán, J., Pena, B., Bailera, M., Eveloy, V., Kannan, P., Raj, A., Lisbona, P., Romeo, L.M., 2022b. Integration of Carbon Capture Technologies in Blast Furnace Based Steel Making: a Comprehensive and Systematic Review. <https://doi.org/10.1016/j.fuel.2022.127074>.
- Pistorius, P.C., Gibson, J., Jampani, M., 2017. Natural gas utilization in blast furnace ironmaking: tuyere injection, shaft injection and prereduction. *Minerals, Metals and Materials Series* 9783319510903, 283–292. [https://doi.org/10.1007/978-3-319-51091-0\\_26](https://doi.org/10.1007/978-3-319-51091-0_26).
- Quarterly Coal Report July–September 2021, 2021. U.S. Department of Energy. <https://www.eia.gov/coal/production/quarterly/pdf/qcr-all.pdf>.
- Romeo, L.M., Pena, B., Bailera, M., Lisbona, P., 2020. Reducing cycling costs in coal fired power plants through power to hydrogen. *Int. J. Hydrogen Energy* 45 (48), 25838–25850. <https://doi.org/10.1016/j.ijhydene.2020.04.095>.
- Ronsch, S., Schneider, J., Matthischke, S., Schluter, M., Gotz, M., Lefebvre, J., Prabhakaran, P., Bajohr, S., 2016. Review on methanation - from fundamentals to current projects. *Fuel* 166, 276–296. <https://doi.org/10.1016/j.fuel.2015.10.111>.
- Rosenfeld, D.C., Bohm, H., Lindorfer, J., Lehner, M., 2020. Scenario analysis of implementing a power-to-gas and biomass gasification system in an integrated steel plant: a techno-economic and environmental study. *Renew. Energy* 147, 1511–1524. <https://doi.org/10.1016/j.renene.2019.09.053>.
- Sahu, R.K., Roy, S.K., Sen, P.K., 2015. Applicability of top gas recycle blast furnace with downstream integration and sequestration in an integrated steel plant. *Steel Res. Int.* 1 (5), 502–516. <https://doi.org/10.1002/srin.201400196>.
- Salehmin, M.N.I., Husaini, T., Goh, J., Sulong, A.B., 2022. High-pressure PEM water electrolyser: a review on challenges and mitigation strategies towards green and low-cost hydrogen production. *Energy Convers. Manag.* 268 (June), 115985. <https://doi.org/10.1016/j.enconman.2022.115985>.
- Sato, M., Takahashi, K., Nouchi, T., Ariyama, T., 2015. Prediction of next-generation ironmaking process based on oxygen blast furnace suitable for CO<sub>2</sub> mitigation and energy flexibility. *ISIJ Int.* 55 (10), 2105–2114. <https://doi.org/10.2355/isijinternational.ISIJINT-2015-264>.
- Sendeco2, 2022. sendeco2. <https://www.sendeco2.com/es/precios-co2%0A>.
- Steelmaking Technologies, 2022. CISDI ingeniering CO. LTD. <http://www.cisdigroup.com/4-steelmaking.html>
- Tomomura, S., 2013. Outline of course 50. *Energy Proc.* 37, 7160–7167. <https://doi.org/10.1016/j.egypro.2013.06.653>.
- Tsupari, E., Karki, J., Arasto, A., Lilja, J., Kinnunen, K., Sihvonen, M., 2015. Oxygen blast furnace with CO<sub>2</sub> capture and storage at an integrated steel mill - Part II: economic feasibility in comparison with conventional blast furnace highlighting sensitivities. *Int. J. Greenh. Gas Control* 32, 189–196. <https://doi.org/10.1016/j.ijggc.2014.11.007>.
- Turner, L.A., 2022. OpenForum2022 (bloomberg) (BNEF) report: 1H 2022 hydrogen market outlook. <https://www.rechargenews.com/energy-transition/will-us-and-european-green-hydrogen-markets-soon-be-flooded-by-cheap-chinese-electrolysers-2-1-1165966>.

- Wu, J., Wang, R., Pu, G., Qi, H., 2016. Integrated assessment of exergy, energy and carbon dioxide emissions in an iron and steel industrial network. *Appl. Energy* 183, 430–444. <https://doi.org/10.1016/j.apenergy.2016.08.192>.
- Zhai, X., Chen, M., 2023. Comparison of data-driven prediction methods for comprehensive coke ratio of blast furnace. *High Temp. Mater. Process.* 42 (1), 16–19. <https://doi.org/10.1515/htmp-2022-0261>.
- Zhang, W., Zhang, J., Xue, Z., 2017. Exergy analyses of the oxygen blast furnace with top gas recycling process. *Energy* 121, 135–146. <https://doi.org/10.1016/j.energy.2016.12.125>.