TECHNO-ECONOMIC ASSESSMENT AND COMPARISON OF DIFFERENT POWER TO GAS INTEGRATIONS FOR THE REDUCTION OF CO_2 EMISSIONS IN THE IRON AND STEEL INDUSTRY

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ABSTRACT

The blast furnace-basic oxygen furnace (BF-BOF) route is currently the dominant process for steel manufacturing, accounting for over 70% of global production. Due to the strong dependency on coal and coke, it is one of the largest industrial emitters of greenhouse gases worldwide (1.8 - 2.0 t_{CO2}/t_{steel}), accounting for 7% of global CO_2 emissions. Different approaches based in power to gas have been investigated in the literature: combustion regime, top gas recycling, use of renewable gaseous fuels and optimization of location of the injection of the renewable fuel.

In the present work, six power to gas concepts have been integrated in a BF-BOF plant and modelled in Aspen Plus. A reference conventional plant of 320 t_{HM}/h (hot metal per hour) has also been modelled for comparison purposes and validated with literature data. The low-carbon cases include (1) amine-based carbon capture and methanation (2) pure oxygen injection instead of air (OBF) added to the previous case, (3) partial top gas recycling added to the previous case, (4) direct methanation of the blast furnace gas under oxy-combustion conditions, (5) CO_2 recycling via lean-H_2 BFG methanation integrated in OBF, and (6) direct injection of hydrogen in an OBF.

The comparative analysis has been performed in terms of key technical and economic parameters, related to fuel consumption rates (448-606 kg_{Coal}/t_{HM}), injection rates of synthetic reducing agents (54-202 kg_{SNG}/t_{HM} or 69 kg_{H2}/t_{HM}), rate of top gas recycling (270 kg_{TGR}/t_{HM}), CO_2 emissions avoided (9-34%), unused steel gases (1827-4542 MJ/t_{HM}), energy penalty (12-18 MJ/kg_{CO2}), electrolyser size (355-1268 MW) and specific costs of CO_2 avoidance (216-352 €/t_{CO2}).

The main conclusion is that case 4, which performs BFG methanation (202 kg_{SNG}/t_{HM}) without carbon capture in an oxygen blast furnace, emerges as the preferred option for decarbonization. While it achieves slightly higher costs (260 €/t_{CO2}) and larger PEM size (972 MW) compared to some other scenarios, it stands out for reduced unused steel gases (1828 MJ/t_{HM}), lower energy penalty (14 MJ/kg_{CO2}), and higher CO_2 avoidance rate (34%). This configuration can cut CO_2 emissions from 1943 kg_{CO2}/t_{HM} to 1286 kg_{CO2}/t_{HM}, without geological storage. In the case of a 320 t_{HM}/h blast furnace, this translates to reducing 210 t_{CO2}/h, or 1680 kt_{CO2} annually. On a global scale, considering steel production in 2020 (1.9 Gt/year) and the BF-BOF route's share (70%), this setup could potentially save as much as 873 million tons of CO_2 per year, about 15% of current global industrial emissions.

1 INTRODUCTION

The blast furnace-basic oxygen furnace (BF-BOF) route is currently the dominant process for steel manufacturing, accounting for over 70% of global production. Due to the strong dependency on coal and coke, it is one of the largest industrial emitters of greenhouse gases worldwide (1.8 - 2.2 t_{CO2}/t_{steel}), being responsible for 7% of global CO_2 emissions (WorlSteel, 2022). Different approaches based in power to gas have been investigated in the literature, varying the combustion regime, top gas recycling, use of renewable gaseous fuels and optimization of location of the injection of the renewable fuel (Ariyama et al. 2016; Zhang et al. 2021; Perpiñán et al., 2023; 2023b). Nevertheless, further research is needed in order to increase the CO_2 abatement, minimizing the economic costs.

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Power to Gas refers to technologies that convert electricity generated from renewable sources into hydrogen or other gaseous and valuable compounds (Götz et al., 2016). These processes involve electrolysis to split water molecules into hydrogen and oxygen. The produced hydrogen can then be further utilized as energy carrier or feedstock for industrial processes. Additionally, the coupling with CO_2 captured from industrial processes allows the production of synthetic methane (Bailera et al., 2021).
In the present paper, from the insight acquired in previous studies, various novel concepts of power to gas are proposed, simulated and compared to assess from the technical and economic point of view the potential of CO_2 emissions reduction in the iron and steel (I&S) industry based in the BF-BOF route.

2 CASE STUDIES

A total of 6 power to gas (PtG) concepts have been integrated in a BF-BOF plant and modelled in Aspen Plus. A reference conventional plant (base case) has also been modelled for comparison purposes and validated with literature data. The low-carbon cases include (1) amine-based carbon capture and methanation (2) pure oxygen injection instead of air (OBF) added to the previous case, (3) partial top gas recycling (TGR) added to the previous case, (4) direct methanation of the blast furnace gas under oxy-combustion conditions, (5) CO_2 recycling via lean-H_2 BFG methanation integrated in an oxygen blast furnace, and (6) direct injection of hydrogen in an oxy-BF. Figure 1 illustrates each configuration.

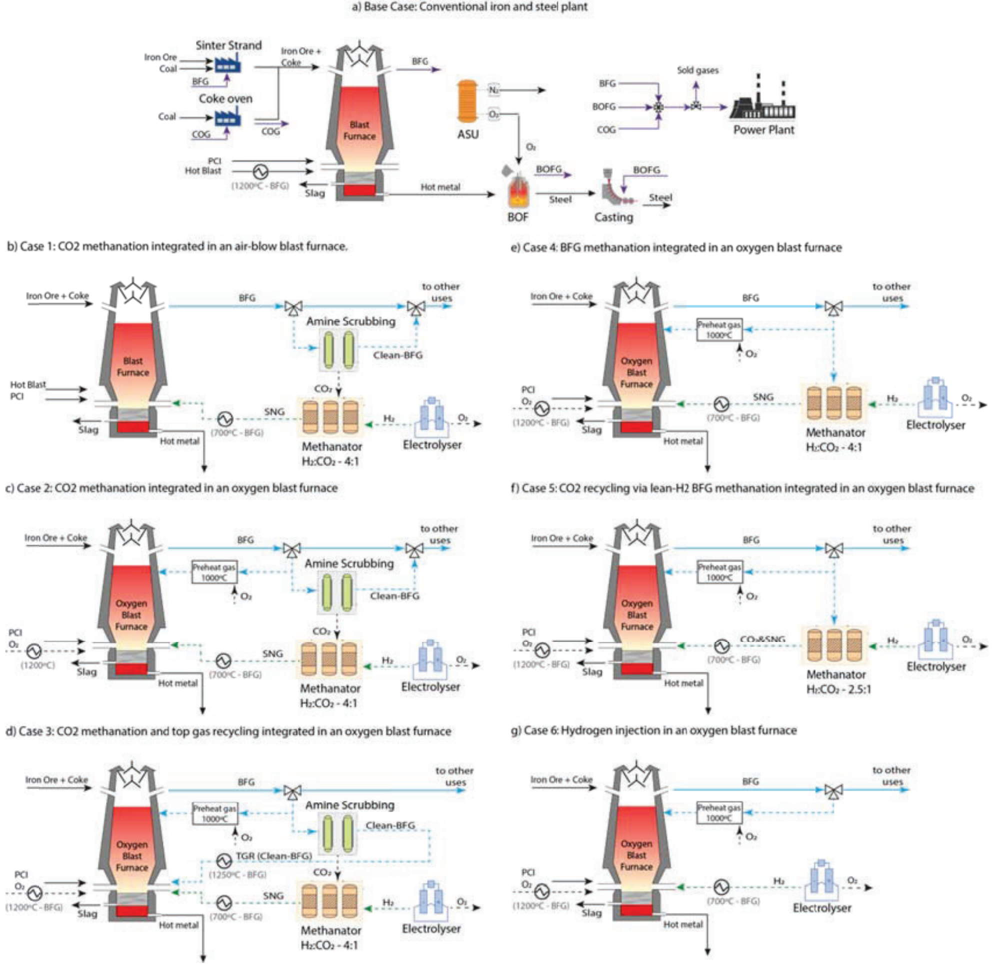

Figure 1. Process flow diagram of the different simulated concepts (details in the text).

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2.1 BF-BOF plant

A conventional I&S plant producing 320 t_{HM}/h (hot metal per hour) is assumed as base case. This reference plant consists of a sinter strand, coke oven, blast furnace (BF, including hot stoves), air separation unit, basic oxygen furnace, the casting-rolling stage and a combined cycle power plant (Figure 1a). The mass flow inputs to the system are iron ore, coal, air, scrap, and flux. Some processes are supplied also with coke oven gas (COG), blast furnace gas (BFG), or basic oxygen furnace gas (BOFG) for producing heat at high temperatures (BFG in the sinter strand and hot stoves, COG in the coke oven, and COG in the basic oxygen furnace). The power plant generates electricity for the I&S plant to be self-sufficient, consuming part of the available COG, BFG and BOFG (100 MWe net power, Wu et al. 2016). The remaining gases are sold to nearby industries.

Each block, modelled and simulated in Aspen Plus, includes essential sub-models for the associated processes. The sinter process represents fine ore particle agglomeration, achieved through initial fusion driven by coal combustion (Babich et al., 2008). The initial step involves heating a blend of iron ore, coal (5 wt%), and limestone to 800 °C utilizing BFG as fuel, followed by coal combustion at 1262 °C to produce sinter (Babich et al., 2008; Wu et al. 2016). The coke oven emulates coal-to-coke transformation in anaerobic conditions. COG combustion (indirect heat exchange) elevates temperature to 1100 °C, yielding coke and coke oven gas. Subsequently, the coke is cooled to 150 °C through coke dry quenching (CDQ).

The BF block includes hot stoves and a simplified blast furnace. In the hot stoves, air is pressurized to 5 bar and indirectly heated to 1200 °C. Within the blast furnace, a first reactor reduces iron oxides to metallic iron, and a subsequent reactor adjusts BFG composition based on CO and H_2 utilization (Eqs.(1)-(2), respectively). Initial parameters include a pulverized coal rate of 150 kg/t_{HM}, H_2 utilization of 0.47, and 4.5wt% carbon content in hot metal (Babich et al., 2008; Bisbas, 1981). Additional parameters (BFG temperature and composition, air and coke flow rates, flame temperature) were derived via a revised Rist diagram (Bailera, 2021b), and subsequently integrated into the Aspen Plus model as inputs.

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

$$\mu_{H2} = H_2O/(H_2O + H_2) \qquad (2)$$

The BOF transforms hot metal (4.5 wt% C) into steel (0.267 wt% C) through O_2 blowing, reacting with carbon to generate CO and CO_2. As this reaction is highly exothermic, 150 kg/t_{HM} of scrap (0.267 wt% C) is introduced to capitalize on this energy (Rönsch et al., 2016). The melted scrap blends with the hot metal, increasing steel production and regulating process temperature (1650 °C). Nitrogen injection from the BOF base promotes mixture stirring. A portion of BOFG preheats the oxygen inlet stream to 1650 °C. O_2 is produced in the ASU via the Hampson-Linde cycle, following an example block in the Aspen Plus repository (Power, Coal gasification, IGCC. The ASU separates oxygen at -189 °C through 94% purity liquefaction.

The Power Plant is simulated as a combined cycle facility, utilizing surplus BFG, COG, and BOFG (100 MWe net power, Wu et al. 2016). The gas power cycle comprises two-stage air compression with intercooling preceding the combustion chamber, along with a single expansion turbine for flue gas. The turbine experiences inlet conditions of 27 bar pressure and 1389 °C temperature. Four counter-current heat exchangers transfer energy from flue gases to steam, reaching a maximum steam temperature of 560 °C. The steam power cycle encompasses three expansion stages, aligned with high, intermediate, and low-pressure turbines.

2.2 Oxygen blast furnace

In Case Studies 2-6, pure oxygen is injected in the BF instead of air, resulting in an oxygen blast furnace (OBF, Ariyama et al., 2008). 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. Temperature drop below

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100 °C can generate significant water condensation concerns/problems. 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. In this study, the required amount of preheating gas is calculated to achieve a temperature of 150 °C in the BFG.

2.3 Amine scrubbing

The amine scrubbing model was developed from a predefined Example File (Shi, 2014). It is adjusted to achieve 90% CO_2 capture from the incoming stream using a 50wt% methyldiethanolamine (MDEA) and water solvent. Prior to entering the capture unit, the water content of the BFG is condensed, and then the gas is diverted to the absorption column.

This absorption column, consisting of 15 stages, has gas entry at the bottom (stage 15) and lean solvent entry at the top (stage 1). Clean gas exits from the top at atmospheric pressure and 42 °C. Rich solvent, laden with CO_2, exits from the bottom at 43 °C and 1.1 bar (loading of 0.2 $\mathrm{kmol_{CO2}/kmol_{MDEA}}$). The rich solvent is then heated to 100 °C in a heat recovery exchanger that cools the lean solvent from the stripper (from 112 °C to 56 °C) before reentering the absorber.

The stripper column, comprising 19 stages with condenser and reboiler stages, further processes the rich solvent. The condenser's reflux ratio is 0.01, and the reboiler's boil-up ratio is 0.1. In the stripper, the rich solvent enters at the second stage and descends as CO_2 is released. The lean solvent exits from the last stage, and CO_2 exits from the first stage. A condenser then cools the CO_2-rich stream from 85 °C to 35 °C, achieving 95vol% CO_2 purity. The condensed solvent is recirculated to the absorber along with the lean solvent.

Ultimately, a makeup stream, mixed with the lean solvent prior to entering the absorber, is introduced to compensate for water and MDEA losses in both the clean gas and CO_2 streams.

2.4 Power to gas plant

In the electrolyzer, water enters at ambient conditions (25 °C and 1 atm), and energy consumption is set at the typical value of 3.8 $\mathrm{kWh/Nm^3H_2}$. The hydrogen outlet stream carries two moles of H_2O per mole of H_2 (which are condensed and recirculated), along with 0.1% of O_2 (purified). The oxygen outlet flow contains minimal traces of hydrogen (0.01%).

Regarding methanation plant, CO_2 from amine scrubbing reacts with H_2 from the electrolyser, producing SNG under stoichiometric conditions. This plant employs two isothermal fixed-bed reactors at 5 bar (Izumiya & Shimada, 2021). The first reactor has an inlet gas temperature of 250 °C and is maintained at 350 °C isothermally. The outlet stream is cooled to 100 °C for water condensation, and then heated to 250 °C before entering the second stage. The second reactor operates at 300 °C. Subsequent to this reactor, water condenses at 25 °C to achieve 95vol% CH_4 in the SNG.

When integrating Power to Gas and amine scrubbing, new thermal streams arise in the process flow diagram. The methanation process provides heat at 300–350 °C, while the CO_2 desorption requires heat at 110–130 °C. Moreover, additional preheating and condensation stages come into operation. Therefore, the proposed concept is thermally integrated using Pinch analysis to reduce the energy penalty. The heat consumption in amine scrubbing (3.1 $\mathrm{MJ/kg_{CO2}}$) can be covered by the exothermic heat of the methanation (6.1 $\mathrm{MJ/kg_{CO2}}$).

2.5 Sizing of the PtG plant

For each case, the maximum amount of reducing gas (SNG, TGR or H_2) is injected, firstly to reduce the pulverised coal injection (PCI) and once it is over, to substitute the coke rate. The amount of reducing gas is limited by the adiabatic flame temperature (AFT), which should not be dropped below 2000 °C for technical reasons. Consequently, the oxygen enrichment increases the AFT and the reducing gas injection lowers it, reaching equilibrium at 2000 °C in the AFT in each case. Thus,

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knowing the amount of reducing gas 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 RESULTS AND COMPARISON OF PtG CONCEPTS

3.1 Comparison of BF performance

A comparative analysis is conducted on the presence of reducing agents in the BF, including coke, PCI, SNG, TGR, H_2, and preheating gas, in both the base case and PtG integrations (Figure 2). In the reference case, consumption stands at 332 kg_{coke}/t_{HM} and 150 kg_{PCI}/t_{HM}. In Case 1 (BF+Amine+Meth.), PCI injection is reduced to 88.8 kg/t_{HM} by injecting 53.6 kg_{SNG}/t_{HM} into an air-blow blast furnace. Cases 2-6 employ an oxygen blast furnace, enabling increased rates of gaseous reducing agents and complete substitution of PCI, alongside partial substitution of coke. Cases 2 (OBF+Amine+Meth.), 3 (OBF+Amine+Meth.+TGR), 4 (OBF+Meth.) and 6 (OBF+H_2) yield coke consumption ranging from 279 to 307 kg_{coke}/t_{HM}. CO_2 injection into the BF's tuyeres assists in AFT control but does not yield significant reductions in fossil fuel consumption. In Case 5 (OBF+Meth.+CO_2), 310 kg_{SNG}/t_{HM} with 35.8% CO_2 injection in the BF results in a coke rate of 426 kg_{coke}/t_{HM}. The preheating gas injection to maintain the BFG temperature at 150 °C ranges from 205 to 260 kg_{BFG}/t_{HM} in the cases involving an oxygen blast furnace (cases 2-6). Notably, the oxygen blast furnace demonstrates a greater reduction in coke consumption compared to the air blast furnace, while CO_2 injection exhibits poor performance. Injection of SNG, TGR, and H_2 produces similar results, with slightly better outcomes for SNG injection (Cases 2 and 4).

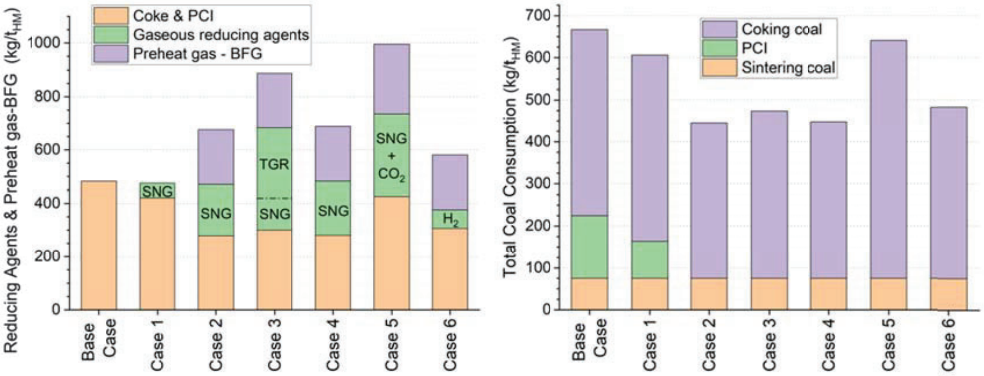

Figure 2. (left) Reducing agents and preheated gas injected in the blast furnace. (right) Total coal consumption.

Regarding the total coal consumption (Figure 2, right) of the I&S industry, PCI is partially substituted in the air blast furnace of Case 1 and fully substituted in the oxygen blast furnaces of Cases 2-6. CO_2 injection in the BF (Case 5) exhibits poor performance, resulting in minimal reduction in total coal consumption. The air blast furnace reduces coal consumption by 9%, while the oxygen blast furnaces (Cases 2-4, and 6) achieve reductions of 28-33%.

3.2 Energy and CO_2 emissions

In the oxygen blast furnaces, higher reducing gas injection leads to larger PEM sizes, as shown in Figure 3 (left). Case 1 (BF+Amine+Meth.) has the smallest PEM size because it requires less SNG compared to the other cases. Conversely, Case 2 (OBF+Amine+Meth.) has the largest PEM size due to the need to methanize substantial CO_2 quantities. Case 3 (OBF+Amine+Meth.+TGR), despite methanizing CO_2, requires almost half the electrolyser size of Case 2 due to the co-injection of large amounts of TGR, reducing SNG requirements. In Cases 4 (OBF+Meth.) and 5 (OBF+Meth.+CO2), methanization of BFG, containing CO and H_2, significantly reduces the demand for green H_2 from the PEM. Case 4 uses an H_2:CO_2 ratio of 4, while Case 5 uses a ratio of 2.5, explaining the lower PEM size in the latter. Case 6 (OBF+H_2) directly injects the H_2 produced by the PEM. The specific power

PEM in MW/(t_{HM}/h), to determine the net/full PEM size, is obtained simply multiplying specific value by the hot metal production, for example 320 t_{HM}/h in the present work.

Regarding oxygen, in Case 1, O_2 produced by the PEM is entirely sold to nearby industries, while in Cases 2-6, the oxygen blast furnace requires large quantities of oxygen. In Cases 2, 4, and 6, where the electrolyser is larger, the air separation unit is not required. However, in Cases 3 and 5, a small ASU, producing 63 and 179 kg_{O2}/t_{HM} respectively, is necessary. These oxygen flows are relatively small when compared to the oxygen consumed by the OBF, ranging from 268 to 437 kg_{O2}/t_{HM}.

It's noteworthy that the PEM size decreases when (i) co-injecting TGR with SNG, (ii) methanizing BFG, and (iii) using a low H_2:CO_2 ratio in the methanation stage. However, the first option requires the additional investment in a small ASU, and the third option usually performs poorly, as unreacted CO_2 is injected into the BF.

The PEM electricity consumption accounts for 78-92% of the total electricity consumption depending on the case, creating a linear dependency between the size of the electrolyser and the total electricity consumption. If an ASU is required it will increase the total electricity consumption, but its consumption is almost negligible with regads to the PEM consumption, barely affecting the results. The electricity consumption is 4965 MJ/t_{HM} for the air blast furnace (Case 1), and between 7925 and 15597 MJ/t_{HM} for the oxygen blast furnaces (Cases 2-6). These figures are higher, compared with the 950 MJ/t_{HM} in the base case and will be determinant in the economic analysis.

The amount of excess gases sold to nearby industries, including BFG, BOFG, and COG, is 2400 MJ/t_{HM} in the base case (Figure left). This value decreases to approximately 1143 MJ/t_{HM} and 1828 MJ/t_{HM} in Cases 3 and 4, where BFG is either used as TGR or directly in the methanation stage. Case 5, despite using BFG in the methanation stage, increases the sold gases to 4227 MJ/t_{HM} due to the higher energy content of BFG, a result of increased coke consumption in the blast furnace. In Cases 1 and 2, where only CO_2 is used in the methanation stage, or in Case 6 with no methanation, the sold gases increase to values ranging from 3278 MJ/t_{HM} to 4542 MJ/t_{HM}. Ideally, lower levels of sold gases are desirable, as this indicates higher plant efficiency. Selling a significant amount of gases may result in the sale of valuable H_2 produced by the electrolyser at a lower price. The best option to have low levels of sold gases is to combine Power to Gas with Top Gas Recycling (Case 3).

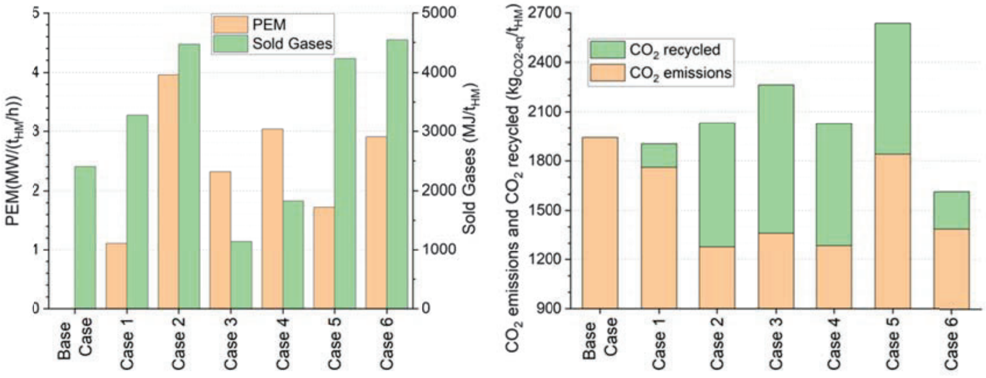

Figure 3. (left) PEM size and sold gases. (right) CO_2 emissions and CO_2 recycled.

As for CO_2 emissions, the integration of PtG into an air blast furnace (Case 1) results in a 9% reduction compared to the base case (1943 kg_{CO2}/t_{HM}, Figure 3, right). For PtG integration into an oxygen blast furnace via SNG injection (Cases 2 (OBF+Amine+Meth.) and 4 (OBF+Meth.)), the CO_2 emission reduction is approximately 34%, the highest among the cases. Slightly lower reductions, around 29%, are observed when using TGR (Case 3) or H_2 (Case 6). When CO_2 is injected into the blast furnace, as in Case 5 (OBF+Meth.+CO_2), the emission reduction is minimal, only 5%. This can be attributed to the coke rate, where higher carbon input as coke leads to increased carbon output in

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the form of CO_2 emissions. Table summarizes the recycling of CO_2 emissions through PtG, TGR, or preheat gas in all analysed cases. Only cases with an oxygen blast furnace have preheating gas, and only Case 3 incorporates TGR. This underscores the importance of maintaining a closed carbon loop, as opening it would significantly increase CO_2 emissions to the atmosphere in most cases.

To contextualize these results, it is essential to consider other low-carbon methods employed in oxygen blast furnace ironmaking, such as top gas recycling. Previous studies have reported CO_2 emissions ranging from 868 to 1180 kg_{CO2}/t_{HM} in the blast furnace for top gas recycling (Bailera et al., 2022). In comparison, the CO_2 emissions from the oxygen blast furnace in the PtG concepts of this study range from 738 to 833 kg_{CO2}/t_{HM} (not to be confused with the total emissions of the entire I&S industry, which range from 1279 to 1387 kg_{CO2}/t_{HM}, as shown in Figure 3, right). Concerning blast furnace emissions alone, the TGR setup shows higher CO_2 flow rates, but a significant portion can potentially be geologically stored (300-700 kg_{CO2}/t_{HM}). Therefore, the environmental impact of the TGR configuration depends on the availability of storage.

Table 1. Breakdown of CO_2 recycling in the base case and PtG integrations.

Case	CO_2 recycled	CO_2 recycled - PtG		CO_2 recycled - TGR		CO_2 recycled – Preheat	
	kg_{CO2}/t_{HM}	kg_{CO2}/t_{HM}	%	kg_{CO2}/t_{HM}	%	kg_{CO2}/t_{HM}	%
Base	0.0	0.0	-	0.0	-	0.0	-
Case 1	143.6	143.6	100	0.0	0	0.0	0
Case 2	751.4	513.2	68	0.0	0	238.2	32
Case 3	902.8	298.8	33	364.6	40	239.3	27
Case 4	740.8	506.3	68	0.0	0	234.5	32
Case 6	796.0	491.0	62	0.0	0	305.0	38
Case 7	227.0	0.0	0	0.0	0	227.0	100

The energy penalty, defined as the net energy consumed in the industry per kilogram of CO_2 avoided through PtG-steelmaking integration, is calculated according to Eq. (3). Detailed units and equation variables are gathered in
Table.

$$E_{penalty} = \frac{\Delta E_{cons} - \Delta E_{coal} \cdot \eta_{elec} - \Delta E_{gases} \cdot \eta_{elec}}{\Delta \dot{m}_{CO2}} \quad [MJ/kg_{CO_2}] \tag{3}$$

Table 2. Description of variables in equation.

Variable	Units	Description
ΔE_{cons}	MJ/t_{HM}	Increase in electricity consumption in the industry
ΔE_{coal}	MJ/t_{HM}	Savings in coal energy
ΔE_{gases}	MJ/t_{HM}	Increase in excess sold gases
$\Delta \dot{m}_{CO_2}$	kg_{CO_2}/t_{HM}	Savings in CO_2 emissions
η_{elec}	-	Energy conversion factor from coal to electricity (0.33)

Figure 4 shows the comparison of the specific energy penalty per ton of CO_2 avoided. It is worth noting that the energy penalty for all PtG cases is relatively high, particularly when compared to amine carbon capture technology, which typically ranges from 3 to 6 MJ/t_{CO2} (Perpiñán et al., 2022). Specifically, when using SNG methanized with CO_2, Case 1 (BF+Amine+Meth.) incurs an energy penalty of 16 MJ/t_{CO2}, while Case 2 (OBF+Amine+Meth.) has an energy penalty of 17 MJ/t_{CO2}. Case 3 (OBF+Amine+Meth.+TGR) exhibits a lower energy penalty of 12 MJ/t_{CO2} because it requires less SNG due to TGR injection, resulting in a smaller PEM size. In Cases 4 (OBF+Meth.) and 5 (OBF+Meth.+CO2), where the BFG being methanized already contains CO and H_2, the PEM size is reduced. However, Case 4 achieves significant CO_2 avoidance with an energy penalty of 14 MJ/t_{CO2}, while Case 5 has less CO_2 avoidance and a higher energy penalty of 60 MJ/t_{CO2}. In Case 6 (OBF+H_2),

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where H_2 is directly used in the oxygen blast furnace without intermediate processes, the energy penalty is 14 MJ/t_{CO2}. In summary, to achieve low energy penalties, it is essential to reduce the PEM size while maintaining effective CO_2 avoidance. The recommended approach to lower the energy penalty is to combine PtG technology with TGR.

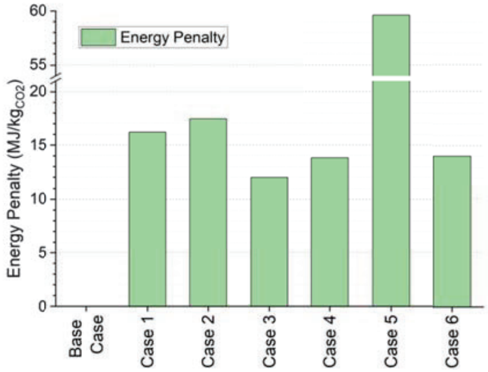

Figure 4. Energy penalty in the base case and PtG integrations. CO_2 recycled include the PtG process, preheat gas injection, and top gas recycling.

3.3 Economic analysis

The economic results of integrating Power to Gas with steelmaking are focused on parameters such as CAPEX, OPEX, Incomes and specific carbon avoidance costs. The analysis assumed a loan amortization period of 20 years, a PtG system operating for 8000 hours per year, a carbon tax value of 84.28 €/t_{CO2}, and a renewable electricity price of 77 €/MWh. 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_2 taxes and coal, and the sold steel gases (BFG, BOFG and COG) and oxygen. The specific cost, in €/t_{CO2} and €/t_{HRC}, is shown in Eqs. (4)-(5). Units and description of equation variables are in
Table.

$$\mathrm{CO_2\ avoidance\ Cost} = \frac{\left(\frac{\mathrm{Capex}}{\mathrm{Loan\ amortization}} + \mathrm{Opex} - \mathrm{Incomes}\right) \cdot 10^6}{\mathrm{CO_2\ avoided} \cdot \mathrm{Operating\ hours}} \qquad \left[\frac{€}{t_{CO_2}}\right] \tag{4}$$

$$\mathrm{Specific\ Implementatio\ Cost} = \frac{\left(\frac{\mathrm{Capex}}{\mathrm{Loan\ amortization}} + \mathrm{Opex} - \mathrm{Incomes}\right) \cdot 10^6}{\mathrm{Iron\ Production} \cdot \mathrm{Operating\ hours}} \qquad \left[\frac{€}{t_{HRC}}\right] \tag{5}$$

Table 3. Description of variables in Eqs. (4)-(5).

Variable	Units	Description
CAPEX	M€	Capital Expenditure
OPEX	M€/year	Operational Expenditure
Incomes	M€/year	Operational Incomes
Loan amortization	Years	Process of paying off a loan over time
CO_2 avoided	t_{CO_2}/h	CO_2 avoided per hour
Operating hours	h/year	Operating hours per year

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Across all cases, the PEM constitutes the largest portion of the CAPEX, accounting for 35% to 43% of the total cost. Purchased electricity is the predominant contributor to the OPEX, making up 94% to 95% of the expenses. The primary source of revenue comes from CO_2 taxes, which range from 33% to 67%. Main economic parameters for Cases 1-6 can be seen in Table 4.

Table 4. Economic parameter for the PtG-steelmaking integration.

Case Study	**CAPEX**	**OPEX**	**INCOMES**	**CO_2 Avoid. Cost**	**Specific Impl. Cost**
	M€	M€/y	M€/y	€/t_{CO2}	€/t_{HRC}
Case 1	268	221	102	283	52
Case 2	1167	835	294	352	233
Case 3	784	490	195	216	130
Case 4	931	640	248	260	171
Case 5	635	397	30	1518	155
Case 6	870	594	288	245	136

In Case 1 (BF+Amine+Meth.), where air blast furnaces allow for smaller quantities of reducing agents and, consequently, smaller PEMs, the specific implementation cost (€/t_{HRC}) is the lowest, as shown in Figure (left). Among the remaining cases with oxygen blast furnaces, Case 3 (OBF+Amine+Meth.+TGR) boasts the lowest specific implementation cost and CO_2 avoidance cost (€/t_{CO2}) due to its smaller electrolyser and high CO_2 avoidance rate. Conversely, Case 5 (OBF+Meth.+CO_2), characterized by a very low CO_2 avoidance rate, experiences a significant increase in the CO_2 avoidance cost, exceeding 1500 €/t_{CO2}. In conclusion, the recommended approach is to combine PtG technology with TGR for more favourable cost outcomes.

It is worth noting that the steel price in 2022 was around 660–1400 €/t_{HRC}, so the specific carbon capture cost represents a 4–35% increase in the actual steel price, depending on the case (9-20% increase for Case 3). However, a recent study conducted by Subraveti et al. (2022), analysed CCS costs in a cement plant (90% capture with a 60% increase in cost) and a steel plant (47% capture with a 13% increase in cost), concluding that the cost increase in a bridge as the final product was only 1%. This implies that the costs incurred for implementing the PtG system in steelmaking, despite being significant, would have a limited impact on the final product competitiveness.

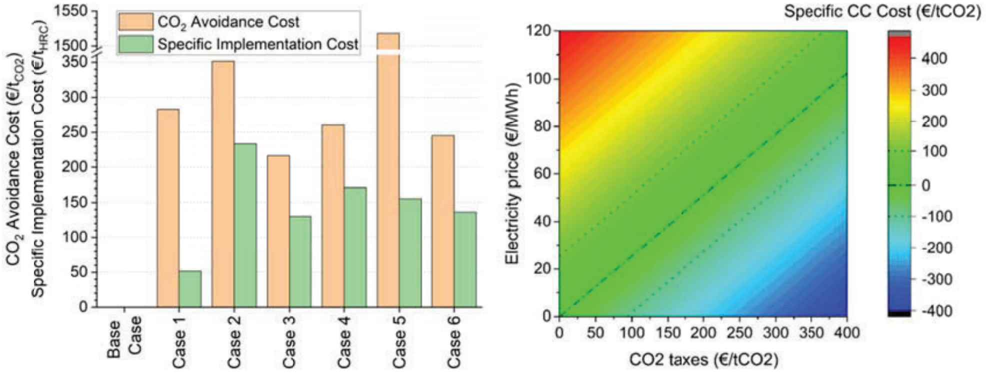

Figure 5. (left) CO_2 avoidance cost (€/t_{CO2}) and specific implementation cost (€/t_{HRC}) in the base case and PtG integrations. (right) Specific CC cost in €/t_{CO2} as a function of the CO_2 taxes and the electricity price for an OBF with two auxiliary fuel injections.

For the case with lower CO_2 avoidance cost, Case 3 (OBF+Amine+Meth.+TGR), a sensitivity analysis was performed (Figure 5, right), considering two auxiliary fuel injections (113 kg_{SNG}/t_{HM} and

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270 kg_{TGR}/t_{HM}), an electrolyser of 741 MW, and an amine scrubbing of 305 kg_{CO2}/t_{HM}. The CO_2 taxes and the electricity price were varied, looking for those combinations that make the PtG-steelmaking integration economically viable. Today, with an electricity price of 77 €/MWh and a CO_2 tax of 84 €/t_{CO2}, the specific CC cost is 216 €/t_{CO2}. Negative costs (i.e., actual benefits) could be achieved under some conditions. For a specific CC cost of 0 €/t_{CO2}, a maximum electricity price of 21 €/MWh should be paid, or a minimum CO_2 tax of 300 €/t_{CO2} should apply. However, these prices or taxes do not guarantee a profitable investment, since the CAPEX should also be amortized. To amortize CAPEX in 20 years (i.e., total investment pay-back of 20 years), the electricity price should be 18 €/MWh, or the CO_2 tax 313 €/t_{CO2}, or an intermediate combination of both parameters, coinciding with a specific CC cost of -13 €/t_{CO2} or -8 €/t_{HM}. With an electricity price of 35 €/MWh (cost of production for wind power), and a CO_2 tax of 150 €/t_{CO2}, the pay-back is 20 years and the investment would be profitable.

4 CONCLUSIONS

In the present paper, six different concepts based Power to Gas technologies has been simulated and assessed from the technical and economic point of view, as potential solution to mitigate CO_2 emissions in the iron and steel industry based in BF-BOF route. Operation parameters has been adjusted in order to be technically feasible.

In Case 1 (BF+Amine+Meth.), the integration of CO_2 methanation within an air-blown blast furnace demonstrated the technical feasibility of the PtG integration system. Nevertheless, the extent of CO_2 reduction achieved is somewhat limited (9% with respect to the conventional plant). The primary constraint on enhancing the reduction in CO_2 emissions lies with the adiabatic flame temperature. As elaborated in the preceding section, despite preheating the reducing agents, they still lower the temperature. Substituting pure oxygen for air (utilizing an oxygen blast furnace) is expected to facilitate the expansion of the PtG facility and, consequently, elevate the rate of CO_2 avoidance.

In Case 2 (OBF+Amine+Meth.), using the same initial setup as in Case 1 but employing an oxygen blast furnace results in substantially increased CO_2 avoidance rates (34% regards conventional plant). However, this improvement comes at the expense of a notable increase in PEM size, energy consumption, and consequently, costs. Given that the primary cost driver is the PEM and its associated electricity usage, it is imperative to explore alternative approaches to address this challenge while preserving a comparable level of CO_2 reduction.

In Case 3 (OBF+Amine+Meth.+TGR), the same configuration as Case 2 is utilized, but with the introduction of TGR. In this setup, the clean-BFG exiting the amine scrubbing process is injected into the tuyeres of the blast furnace. This action leads to a significant reduction in the H_2 requirements at the methanation plant, resulting in a noteworthy decrease in PEM size and achieving the lowest carbon avoidance costs among all cases. The CO_2 avoidance rate remains high (about 29%), with a slight decrease compared to Case 2. Furthermore, the implementation of TGR technology leads to a substantial reduction in the volume of gases sold, enhancing overall efficiency and preventing the sale of unused renewable gases from the BF.

In Case 4 (OBF+Meth.), the injection of BFG, primarily composed of CO_2, CO, and H_2, is injected directly in the methanation plant. The objective is to decrease the production of green H_2 from the electrolyser and reduce the volume of gases sold. The reduction in PEM size, which leads to energy and cost savings, is substantial compared to Case 2 but not as pronounced as in Case 3. Nevertheless, this specific configuration has achieved CO_2 reductions similar to those in Case 2.

In Case 5 (OBF+Meth.+CO_2), the objective is to reduce the consumption of H_2 in methanation and increase the recycling of CO_2, thereby avoiding CO_2 emissions. To achieve this, the H_2:CO_2 ratio in the methanation process is set to 2.5. However, the results were unfavourable due to the strong endothermic nature of CO_2 when injected into the blast furnace. While the PEM size did decrease, coke consumption increased significantly compared to Case 4. This led to very low CO_2 avoidance

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rates along with a substantial increase in energy penalty and costs. It is advisable to minimize the injection of CO_2 into the blast furnace whenever possible.

In Case 6 (OBF+H_2), the goal is to create a simpler configuration without recirculations or loops and to avoid thermal losses in the methanation process. Here, the H_2 produced in the PEM is directly injected into the blast furnace. While the amount of CO_2 avoided is lower than in Cases 2-4, the carbon avoidance costs are slightly above Case 3. Due to the absence of BFG utilization in the methanation process, a significant portion of the unreacted H_2 from the blast furnace is sold at a lower price, resulting in a higher volume of sold gases.

In conclusion, our analysis suggests that the recommended approach is Case 4, which performs a BFG methanation without carbon capture in an oxygen blast furnace. This configuration, while obtaining slightly higher costs compared to some other cases, stands out as the most favourable. It features the highest carbon avoidance rates, with moderate energy penalty and sold gases.

The PtG-steelmaking configurations analysed in this study apply in situations where CO_2 storage is not available and shaft injection in the blast furnace is not considered. If we consider these options, other possible configurations can be analysed in future research.

NOMENCLATURE

The nomenclature should be located at the end of the text using the following format:

AFT	adiabatic flame temperature	I&S	iron and steel
ASU	air separation unit	MDEA	methyldiethanolamine
BF	blast furnace	OBF	oxygen blast furnace
BFG	blast furnace gas	O&M	operation and maintenance
BOF	basic oxygen furnace	PCI	pulverized coal injection
BOFG	basic oxygen furnace gas	PtG	power to gas
CDQ	coke dry quenching	SNG	synthetic natural gas
COG	coke oven gas	TFG	top gas recycling
IGCC	integrated gasification combined cycle		

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