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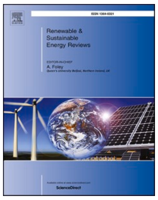

Outline of all potential Power to Gas integrations in blast furnace ironmaking: A systematic review

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ABSTRACT

This work presents the first systematic review analysis of potential Power to Gas integrations in blast furnace ironmaking. The primary objective of the paper is to evaluate the PtG technology implementation in both conventional air-blown and full oxygen blast furnaces, considering different BFG recycling routes (upper, shaft or tuyeres), and synthetic gases (SNG, H2 or syngas). Employing a systematic methodology, the paper compares all the studies using 14 Key Performance Indicators (KPI) and elaborates a discussion on the main findings and limitations, proposing areas for future research. PtG application enables air-blown blast furnaces to cut emissions to 1060 kg_{CO2}/t_{HM}. With PtG and top gas recycling, oxygen blast furnaces achieve a reduction to 747 kg_{CO2}/t_{HM}, and when combined with geological storage, the reduction further drops to 435 kg_{CO2}/t_{HM}. Additionally, the authors propose a novel PtG-ironmaking integration based on the findings of this paper.

Nomenclature

Abbreviation	Meaning
AFT	Adiabatic Flame Temperature
ASU	Air Separation Unit
BF-BOF	Blast Furnace-Basic Oxygen Furnace
BFG	Blast Furnace Gas
BOFG	Basic Oxygen Furnace Gas
CC	Carbon Capture
CCUS	Carbon Capture Utilization and Storage
DRI	Direct Reduced Iron
HM	Hot Metal
I&S	Iron and Steel
IEA	International Energy Agency
PEM	Proton Exchange Membrane
PtG	Power to Gas
PCI	Pulverized Coal Injection
RA	Reducing agent
SNG	Synthetic Natural Gas
tHM	Ton of Hot Metal
tCS	Ton of Crude Steel
TGR	Top Gas Recycling
TRL	Technology Readiness Level

1. Introduction

Iron and steel production is essential for modern society, providing a wide range of applications in construction, transportation, and manufacturing. However, due to the industry's heavy reliance on fossil fuels, it is also one of the largest emitters of greenhouse gases worldwide (1.8–2.0 t_{CO2}/t_{steel}), accounting for 7 % of global CO_2 emissions [1]. Reducing its carbon footprint is a significant challenge when aiming for the global climate change mitigation goals.

The blast furnace-basic oxygen furnace (BF-BOF) route is currently the dominant process for steel manufacturing, accounting for over 70 % of global production. The process starts with the preparation of raw materials (iron ore, coke, and limestone). The iron ore is first mined, then crushed into small pieces, and finally treated in the sinter strand. In sintering, iron ore fines are agglomerated with other fine materials (5–7 mm in size) by combusting coal, in order to obtain a 50 mm open-grained, consistent material with definite basicity optimal for the blast furnace [2]. Coke is made from coal in the coke ovens. Here, coal is heated to 1100 °C in an oxygen deficient atmosphere (carbonization process) to drive off the volatile products and leave a solid residue that mainly consists of carbon (i.e., coke). Coke is the most important raw material in blast furnaces since it is used to reduce the iron ore [3]. Lastly, limestone is calcined to obtain lime. Lime has different uses

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within the steel industry, such as binder in the production of sinter, desulfurizing agent in the blast furnace, slag forming component to remove impurities, and component to control melt chemistry to reduce the damage in furnace linings [4].

Once the raw materials are prepared, they are fed into the blast furnace at the top. The furnace is typically 34 m in height, 16 m in diameter, and lined with refractory materials [5,6]. At the lower part, hot air is blown into the furnace through tuyeres. The coke burns with the oxygen of the hot blast, thus providing the process with heat and CO-reducing gas (this gas reduces the iron oxides in counter-current while ascending). The molten iron is then tapped off from the bottom of the furnace and transported to a basic oxygen furnace (BOF) for further refining into steel. In the BOF, the carbon content of the molten iron is decreased by injecting pure oxygen, which oxidizes de carbon thus forming CO and CO_2. The heat released in this process is used to melt scrap, which is combined with the hot metal at the beginning of the BOF process. After the steel is refined, it is cast into various shapes and sizes, such as billets, slabs, or sheets, depending on the final application. The steel is then cooled and processed through various finishing techniques, such as rolling, cutting, and coating.

Despite the BF-BOF route has been optimized over the years to increase its efficiency and reduce its emissions, it still relies heavily on fossil fuels and is responsible for significant emissions of CO_2 and other greenhouse gases. To address the challenges posed by the BF-BOF process, alternative methods for steel production are being developed. One such method is the oxygen blast furnace (OBF), which uses pure oxygen instead of air to burn coke, reducing the amount of fuel required (lower emissions) and resulting in higher energy efficiency. Additionally, top gas recycling (TGR) can be used to further reduce emissions in the BF-BOF process. TGR involves the capture and recycling of the gases produced during the hot metal production, such as carbon monoxide and hydrogen, back into the process as reducing agent. This not only reduces emissions (by up to 40–55 % [7]) but also increases energy efficiency and can lead to cost savings.

Another promising technology that can contribute to decarbonizing the steel industry is power to gas (PtG) [8]. PtG technologies convert renewable electricity surplus into hydrogen, syngas or synthetic natural gas (SNG) using electrolysis and methanation processes. These gases can then be used as low-carbon fuels or feedstocks for the steel industry. PtG technologies can help to balance the intermittency of renewable electricity sources, to provide flexibility to the electricity grid, and to decarbonize the steel industry.

Few studies were found that apply power to gas technology in the blast furnace-basic oxygen furnace steel production route. Among them, only two papers have focused on substituting the fossil natural gas used in industry processes such as casting or reheating, rather than in the blast furnace. These studies injected synthetic gas into these specific processes, separate from the blast furnace. Rosenfeld [9] studied an electrolyzer and methanation systems coupled with a biomass gasification plant (105 MW_{th}), where the steel gases were used as the CO_2 source for methanation. Medved [10] studied different scenarios, including (i) methanation of all BFG and BOFG, (ii) substitution of fossil NG with BFG and BOFG methanation, and (iii) substitution of fossil NG with BOFG methanation, where the H_2 was produced in a PEM and a biomass gasification plant (100 MW_{th}).

A first approach of power to gas implemented in the blast furnace process was done by the Tokyo Institute of Technology, Japan. Throughout a series of studies [11–14], a novel process combining a nuclear HTGR (high-temperature gas-cooled reactor) with a SOEC electrolyser was proposed to reduce CO_2 into CO, which is later used to reduce the iron oxides. Hisashige et al. [15] performed an exergy analysis combining a PSR (Partial Smelting Reduction process) with top gas recycling, obtaining a maximum CO_2 emission decrease of 22 %.

Prior reviews in the field were overly broad, covering green and low-carbon ironmaking technologies [16], exclusively examining the impact of renewable gases without encompassing the entire Power to Gas chain [17,18], or investigating Power to X technologies within the I&S industry [8], rather than focusing specifically on Power to Gas in the blast furnace. Therefore, this review aims to fill that gap by summarizing information on this specific topic, presenting key findings, and suggesting future research directions.

This study outlines all the potential integrations of power to gas technology in blast furnace ironmaking. Firstly, it explains in detail different ways to implement the power to gas technology in both the conventional air-blown blast furnace and the full oxygen blast furnace, Section 3. These two options consider different BFG recycling routes (upper, shaft or tuyeres), and different synthetic gases (SNG, H_2 or syngas). Then, a systematic review is performed to find all the power to gas configurations studied in literature, Section 4. Finally, all the studies are compared using 14 Key Performance Indicators (KPI), Section 5. This work concludes with a discussion of the main findings and limitations, and proposes areas for future research, Section 6.

2. Methodology

2.1. Systematic review

To find the most relevant literature on Power to Gas integrations in blast furnace ironmaking, a systematic approach was implemented. Web of Science was selected as the search engine because of its advanced search capabilities and wide range of databases. The search is limited to studies presented in scientific journals and conferences included in the selected search engine. Two sets of words were used in the search (Table 1), the first one with terms related to blast furnaces, and the second one with terms related to Power to Gas. The search was done for the title, abstract and keywords, and returned a total of 78 entries, which were screened based on their abstract [19], and selected for examination when applying any type of Power to Gas on the blast furnace, leading a total of 14 articles.

Articles purely related to CO_2 emission reduction, fuel consumption reduction, methane production for sale or hydrogen production were not included in this analysis. Articles that does not recycle carbon through power to gas, or does not focus on the blast furnace, were also not considered.

2.2. Key performance indicators

The key performance indicators quantify the most important aspects that affect the overall performance of the system (Table 2). These serve to compare the different integrations of power to gas in blast furnace ironmaking. The first four KPIs are the fuel consumptions in the blast furnace (KPI01: coke; KPI02: pulverized coal; KPI03: total coal; and KPI04: synthetic gases). Characterizing the fuel consumption is essential as it affects both the economic and the environmental performance of the blast furnace. In the case of KPI03, Eq. (1) is used, where 1.33 kg of coking coal is typically required to produce 1 kg of coke [20].

$$KPI_{03} = Total\ coal\ consumption = PCI + Coke \times 1.33 \tag{1}$$

The KPI05 measures the amount of top gas that is recycled (at either tuyeres, shaft or upper part). Quantifying the gas recycled is important as it affects to the availability of fuel gas for self-consumption in the rest

Table 1
Search terms, number of hits returned and number of papers reviewed.

Search term	Hits	Reviewed
(“Ironmaking” OR “steelmaking” OR “Iron and steel” OR “blast furnace” OR “steel industry”)	325	14
(“Power-to-Gas” OR “power to gas” OR “PtG” OR “power to methane” OR “synthetic natural gas” OR “power to H2″ OR “power to hydrogen” OR “PtH2″ OR “CO2 electrolysis” OR “power to syngas” OR “power-to-syngas” OR “H2 injection” OR “hydrogen injection” OR “methanation”)		

Table 2

Main KPIs for power to gas integrations in blast furnace ironmaking.

KPI	Variable	Units
KPI01	Coke rate	kg_{Coke}/t_{HM}
KPI02	PCI rate	kg_{PCI}/t_{HM}
KPI03	Total coal consumption (PCI + coking coal)	kg_{Coal}/t_{HM}
KPI04	Synthetic RA injected in BF (SNG, H_2, syngas)	kg_{RA}/t_{HM}
KPI05	Top gas recycled in BF	kg_{TGR}/t_{HM}
KPI06	Adiabatic Flame Temperature (AFT)	°C
KPI07	CO_2 emissions (BF)	kg_{CO2}/t_{HM}
KPI08	CO_2 to geological storage	kg_{CO2}/t_{HM}
KPI09	Excess steel gases (sold or flared)	MJ/t_{HM}
KPI10	Energy Penalty	MJ/kg_{CO2}
KPI11	Electrolyser size	$MW/(t_{HM}/h)$
KPI12	O_2 produced in the ASU	kg_{O2}/t_{HM}
KPI13	CO_2 avoidance cost	$€/t_{CO2}$
KPI14	Specific implementation cost	$€/t_{HM}$

of the plant. It must be noted that when injecting top gas in the tuyeres or shaft (TGR), carbon capture is recommended in order to not inject CO_2. However, when injecting top gas in the upper part, raw BFG can be used since CO_2 has minor influence at this stage. The KPI06 considers the adiabatic flame temperature (AFT). This parameter is controlled to guarantee that it is 2000 °C or higher (technical constrain) [21]. The KPI07 and KPI08 are the CO_2 emissions exiting the blast furnace, and the CO_2 sent to geological storage, respectively. The former considers all $CO_{2\text{-}eq}$ out of the BF's limits, including the $CO_{2\text{-}eq}$ from the CO (assuming that it will be burned to CO_2 eventually) and the pure CO_2 for geological storage, but excluding the recycled $CO_{2\text{-}eq}$ through TGR and PtG, according to Fig. 1. The KPI09 quantifies the excess of fuel gases from the ironmaking processes, which could be sold (or should be flared). If this KPI is above 0, it means that there are enough steel gases to satisfy the energy requirements of the downstream processes (sintering, coke oven, power plant, etc.). However, if KPI09 is below 0, the ironmaking plant will not be self-sufficient in thermal energy consumption. For the calculation of KPI09, a power plant of 100 MW_e and 36 % efficiency was assumed [22]. The KPI10 shows the energy penalty of the power to gas integration in blast furnace ironmaking, which is the additional energy consumed compared to the base case per kg of CO_2 avoided. This parameter is the basis for comparison between all the potential configurations and other technologies. The KPI11 is the maximum size of electrolysis that can be integrated (usually limited by the decrease in flame temperature, which is caused by the injection of synthetic gas). This value is given as a function of the size of the blast furnace, since scale-effects are not considered in the simulation. The KPI12 is the O_2 produced in the air separation unit to supply the different processes of the ironmaking plant (e.g., BF and BOF). When integrating power to gas, this value decreases thanks to taking advantage of the O_2 produced in the electrolyzer. If KPI12 drops to cero, it means that the ASU is no longer needed. Lastly, the KPI13 and KPI14 are the cost of integrating power to gas, per ton of CO_2 avoided (Eq. (2)) and per ton of hot metal produced (Eq. (3)), respectively.

$$CO_2\ avoidance\ cost = \frac{\left(\frac{Capex}{Loan\ amortization} + Opex - Incomes\right)\cdot 10^6}{CO_2\ avoided \cdot Operating\ hours} \quad \left[\frac{€}{t_{CO_2}}\right] \tag{2}$$

$$Specific\ Implementation\ cost = \frac{\left(\frac{Capex}{Loan\ amortization} + Opex - Incomes\right)\cdot 10^6}{Iron\ Production \cdot Operating\ hours} \quad \left[\frac{€}{t_{HM}}\right] \tag{3}$$

3. Outline of all potential power to gas integrations in blast furnace ironmaking

The outline of all potential integrations is the result of combining the different approaches that can be follow when integrating power to gas, in terms of (i) combustion regime, (ii) top gas recirculation, (iii) renewable gas produced, and (iv) location of the injection of the renewable gas:

- Combustion regime (2 options):
  - o Air-blown
  - o Oxy-fuel
- Type of top gas recirculation (8 options, see Fig. 2A):
  - o No recirculation
  - o Single, located at
    - Tuyeres
    - Shaft
    - Upper zone
  - o Double, located at
    - Tuyeres and shaft
    - Tuyeres and upper zone
    - Shaft and upper zone
  - o Triple, located at
    - Tuyeres, shaft and upper zone
- Type of renewable gas produced (5 options, see Fig. 2B):
  - o Synthetic natural gas from the methanation of
    - Pure CO_2 from amine scrubbing
    - Sweet gas from amine scrubbing
    - Blast furnace gas
  - o Hydrogen from electrolysis
  - o Syngas from CO_2 electrolysis
- Injection location of the renewable gas (3 options):

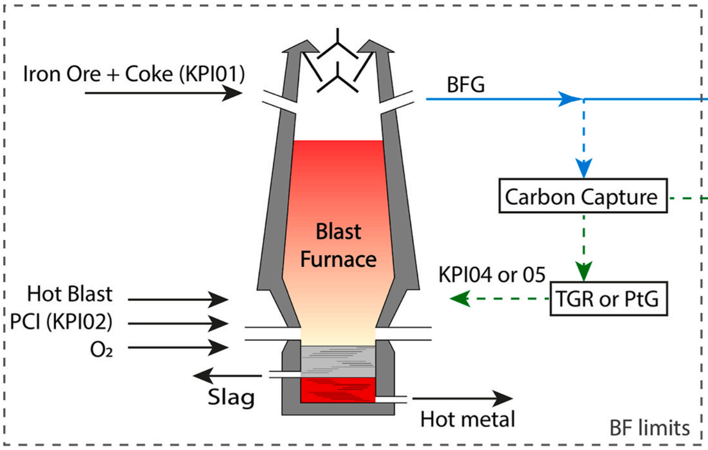

Fig. 1. Simplified process flow diagram of a blast furnace with top gas recycling (or power to gas), showing some of the KPIs considered for this analysis (Table 2).

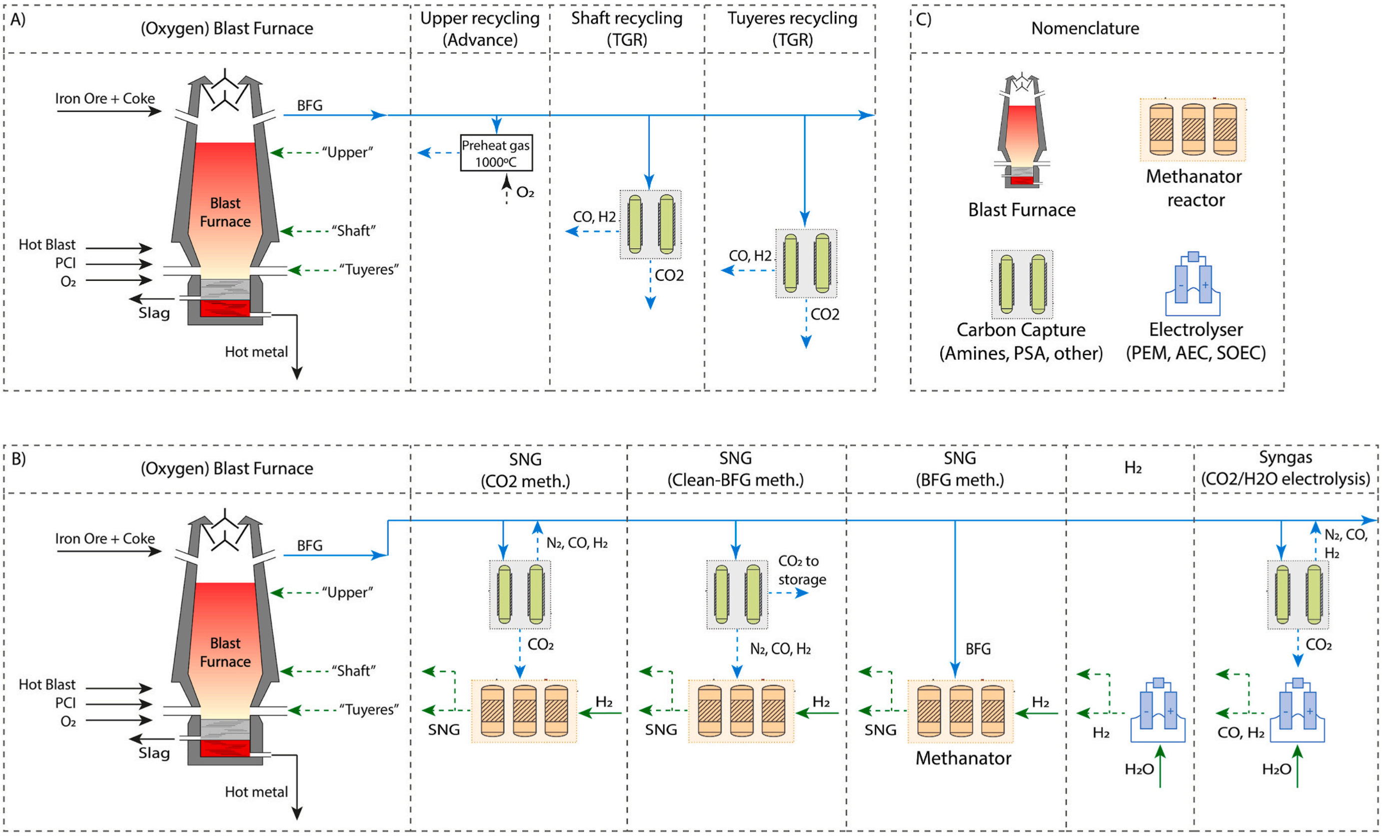

Fig. 2. Summary of the different options for blast furnace ironmaking when integrating power to gas, in terms of A) gas recycling, and B) renewable gas injection. Nomenclature appears in C).

  - o Tuyeres
  - o Shaft
  - o Tuyeres and shaft

Considering all the options, the entire outline gathers 240 integration configurations (2 regimes × 8 top gas recyclings × 5 renewable gases × 3 injection locations). Table 3 summarises all these possible configurations, indicating the configurations that were already studied in literature, and identifying the configurations that are not worth studying because of the expected low performance. The latter are those that end up injecting large N_2 contents in the blast furnace, leading to remarkable drops in the adiabatic flame temperature and low fossil fuel replacement ratios, with the additional problem of the nitrogen build-up [23]. This happens under air-blown regimes when the top gas is recycled or when methanation consumes blast furnace gas without prior separation. Using oxy-fuel regimes prevents these problems, since the N_2 concentration of the BFG drops to 1 %–2 %. Moreover, the recirculation of CO_2 is not recommended for the same reasons. This may occur if methanation is carried out under sub-stiochiometric ratios (H_2:CO_2 < 4) [24], if CO_2 electrolysis has low conversion [6], or if top gas recycling is perfomed without prior carbon capture to reject the CO_2 from the BFG [25] (please note that none of these 3 possibilities are considered in the outline).

For many of the integrations presented in Table 3, readers may consider additional options, such as:

- Technology for H_2 production:
  - o PEM
  - o Alkaline
  - o SOEC
  - o Biomass gasification
- Fossil fuel replaced by the renewable gas:
  - o Coke
  - o Coal
- Temperature of the O_2 and renewable gases before injection:
  - o From 25 °C to 1250 °C
- Source of the electricity (and its price):
  - o Renewable
  - o Fossil
- Carbon capture technology:
  - o Amine scrubbing
  - o Calcium looping
  - o PSA
  - o Other

These are just a few examples of the differences that can be found when analysing a specific configuration, showing the vast knowledge gap, even for those cells of Table 3 that were already studied in literature. However, we do not deelve into these options, as the total outline would increase to more than 15,000 possibilities of integration. The comparison and discussion of the following sections is limited to those aspects that really brings innovation to the process. Still, some comments are worth to mention regarding these additional options.

Regarding the technology for renewable H_2 production, the most extended technologies are PEM and Alkaline electrolysis, but it can also be obtained from the gasification/pyrolysis of biomass. The main limitation of biomass is the availability of the resource, since power to gas requires large quantities of hydrogen. Another problem might be the presence of impurities in the H_2 or syngas obtained from the biomass, which could damage the methanation catalyst. An alternative to H_2 is the utilization of CO as reducing agent, obtained from the electrolysis of CO_2 supplied with renewable electricity. The limitation in this case is the

Table 3
Summary of the outline of all potential power to gas integrations in blast furnace ironmaking. The type of renewable gas produced is denoted by A (SNG from pure CO_2), B (SNG from sweet gas), C (SNG from BFG), D (H_2), and E (Syngas from CO_2 electrolysis). The configurations not recommended are marked with *. References are included for the configurations studied in literature.

Combustion regime: Air-blown			
Type of top gas recirculation	Injection location of the renewable gas:		
	Tuyeres	Shaft	Tuyeres & Shaft
No recirculation	A [20,26], B* [26], C* [26], D [26–28], E [6,29]	A, B*, C*, D, E	A, B*, C*, D, E
Single			
Tuyeres	A*, B*, C*, D*, E*	A*, B*, C*, D*, E*	A*, B*, C*, D*, E*
Shaft	A*, B*, C*, D*, E*	A*, B*, C*, D*, E*	A*, B*, C*, D*, E* [30]
Upper	A*, B*, C*, D*, E*	A*, B*, C*, D*, E*	A*, B*, C*, D*, E*
Double			
Tuyeres & shaft	A*, B*, C*, D*, E*	A*, B*, C*, D*, E*	A*, B*, C*, D*, E*
Tuyeres & upper	A*, B*, C*, D*, E*	A*, B*, C*, D*, E*	A*, B*, C*, D*, E*
Shaft & upper	A*, B*, C*, D*, E*	A*, B*, C*, D*, E*	A*, B*, C*, D*, E*
Triple			
Tuyeres & shaft & upper	A*, B*, C*, D*, E*	A*, B*, C*, D*, E*	A*, B*, C*, D*, E*
Combustion regime: Oxy-fuel			
Type of top gas recirculation	Injection location of the renewable gas:		
	Tuyeres	Shaft	Tuyeres & Shaft
No recirculation	A, B, C, D, E	A, B, C, D, E	A, B, C, D, E
Single			
Tuyeres	A [26,31], B [26], C [25,26], D [26], E	A, B, C, D, E	A, B, C, D, E
Shaft	A, B, C, D, E	A, B, C, D, E	A, B, C, D, E
Upper	A [32], B, C [24], D [24], E	A, B, C, D, E	A, B, C, D, E
Double			
Tuyeres & shaft	A, B, C, D, E	A, B, C, D, E	A, B, C, D, E
Tuyeres & upper	A [33], B, C, D, E	A, B, C, D, E	A, B, C, D, E
Shaft & upper	A, B, C, D, E	A, B, C, D, E	A, B, C, D, E
Triple			
Tuyeres & shaft & upper	A, B, C, D, E	A, B, C, D, E	A, B, C, D, E

high electricity consumption, the low TRL (5–6) and the limited CO_2 conversion (60 %–70 % [6,29]). Syngas production with low CO_2 conversion ratios leads to the direct injection of CO_2 into the blast furnace's tuyeres, what cools the adiabatic flame temperature rapidly [24]. Authors recommend in descending order of priority (i) the use of biomass as a hydrogen/syngas source when available, for direct injection (no methanation); (ii) the use of SOEC for CO_2 electrolysis coupled with a methanation stage (to fully convert the unreacted CO_2) if high TRL is reached; (iii) the use of a PEM/Alkaline electrolyser, for H_2 direct injection or SNG production.

In terms of fossil fuel replacement, the substitution ratio of coal is usually greater than for coke, so coal replacement allows injecting larger amounts of reducing agent. This leads to greater emission reductions and lower energy penalties [26]. Additionally, the temperature at which the oxygen and reducing gases are preheated affects to the amount of gas that can be injected. The higher the injection temperature, the higher the adiabatic flame temperature, and the greater the amount of reducing agent that can be used [32]. For instance, the ULCOS project injects the top gas recycled at 1250 °C [34]. Regarding carbon capture, the process is typically expensive and energy-consuming, independently of the technology chosen. Nevertheless, synergies are found in the case of amines, whose energy needs can be supplied with the exothermal heat from methanation [20]. Therefore, if carbon capture is required for the proper integration of power to gas, amine scrubbing should be chosen. Moreover, putting the cost in perspective, the capital expenditure of carbon capture is low compared with that of the electrolyser or cost of retrofitting a blast furnace. Therefore, despite there are a few configurations that do not need a carbon capture stage (e.g., those that use H_2, or that directly methanize the BFG), these should not be necessarily prioritized since they might not offer a significant advantage in terms of CO_2 avoidance or costs.

4. Review on power to gas integrations in blast furnace ironmaking

After applying the methodology of systematic review explained before, and classifying the different integrations according to the proposed outline, 14 different scientific papers were found dealing with the implementation of power to gas technology in the iron and steel industry (Table 4). These papers are summarized in the following subsections, distinguishing between air-blown and oxygen blast furnaces.

4.1. Power to gas integrations in air-blown blast furnaces

Six power to gas configurations were studied in literature for air-blown blast furnaces (Fig. 3). According to the outline, three of these integrations are not recommended because they recirculate large amounts of N_2 into the furnace. These are:

- No TGR, with SNG (from sweet gas) injected in tuyeres: Bailera et al. [26] studied four configurations within the air-blown blast furnace without recycling, including SNG production with CO_2 methanation, sweet BFG methanation, BFG methanation, and H_2 production as a reducing agent injected in the tuyeres. They focused on the blast furnace modelling and the influence of the SNG mass flow rate when replacing coal or coke, analysing up to 17 different KPIs as a function of the electrolysis power capacity ($MW/(t_{HM}/h)$). For the case of

Table 4
Summary of the integration options for power to gas in ironmaking that were studied in literature, classified according to the outline of Table 3.

	Air-blown blast furnace	Oxygen blast furnace
Not recommended integrations	3 out of 111	n/a
Recommended integrations	3 out of 9	8 out of 120
Total	6 out of 120	8 out of 120

Table 5

Main KPIs for reviewed PtG integrations in blast furnaces (KPI definition in Table 2). Ref: Typical reference values.

Combustion regime	Renewable gas	Type of top gas recirculation	KPI01	KPI02	KPI03	KPI04	KPI05	KPI06	KPI07	KPI08	KPI09	KPI10	KPI11	KPI12	KPI13	KPI14	Ref.
			kg_{Coke}/t_{HM}	kg_{PCI}/t_{HM}	kg_{Coal}/t_{HM}	kg_{RA}/t_{HM}	kg_{TGR}/t_{HM}	°C	kg_{CO2}/t_{HM}	kg_{CO2}/t_{HM}	MJ/t_{HM}	MJ/kg_{CO2}	$MW/(t_{HM}/h)$	kg_{O2}/t_{HM}	$€/t_{CO2}$	$€/t_{HM}$	–
Air	–	No recirculation	289–332	150–200	534–641	0	0	2258	1300–1400	0	2400–2700	–	–	87–95	–	–	Ref.
Air	SNG (CO_2)	No recirculation	332	88.8	531	53.6	0	2000	1187	0	3278	17.8	1.81	0	283	52	[20]
			289	115	500	65.2	0	2000	1100	0	3467	19.8	1.59	0	–	–	[26]
Air	SNG (sweet gas)	No recirculation	289	157	541	140	0	2000	1210	55	2567	12.8	0.61	0	–	–	[26]
Air	SNG (BFG)	No recirculation	289	141	526	133	0	2000	1190	0	3067	14.7	0.86	0	–	–	[26]
Air	H_2	No recirculation	289	103	488	33.4	0	2000	1060	0	3517	18.5	1.67	0	–	–	[26]
			390	0	518	27.5	0	2150	1063	0	–	–	1.58	0	–	–	[27]
			327	112	546	20	0	2000	1182	0	–	–	0.88	–	–	–	[28]
Air	Syngas	No recirculation	288	85	467	140	0	–	1238	0	–	–	–	–	–	–	[6]
			359	101	579	89	0	–	1320	0	–	37.9	0.22	–	–	–	[29]
Air	Syngas	Shaft recycling	275	137	503	188	91	–	1129	216	3523	–	2.22	58	–	–	[30]
Oxy-fuel	–	Tuyeres recycling	150–367	0–400	470–655	0	449–950	2000–2400	868–1180	300–700	−3300–767	–	–	250–350	–	–	Ref.
Oxy-fuel	SNG (CO_2)	Tuyeres recycling	235	120	432	61.5	408	2000	925	215	1267	17.8	1.50	100	–	–	[26]
			261	155	502	22	600	2014	1067	378	–	17.9	0.54	253	–	–	[31]
Oxy-fuel	SNG (sweet gas)	Tuyeres recycling	235	115	427	62.9	414	2000	925	490	267	10.0	0.98	180	–	–	[26]
Oxy-fuel	SNG (BFG)	Tuyeres recycling	235	115	427	62.2	411	2000	910	390	1057	12.5	1.18	150	–	–	[26]
			370	0	492	65	1022	–	1250	0	470	34.0	1.35	180	–	–	[25]
Oxy-fuel	H_2	Tuyeres recycling	235	111	423	24.4	321	2000	905	340	887	13.6	1.22	90	–	–	[26]
Oxy-fuel	SNG (CO_2)	Upper recycling	279	0	370	192	205	2000	738	0	4470	17.5	3.96	0	352	233	[32]
Oxy-fuel	SNG (BFG)	Upper recycling	280	0	372	202	205	2000	747	0	1828	13.8	3.03	0	260	171	[24]
Oxy-fuel	H_2	Upper recycling	307	0	408	69	205	2000	833	0	4542	14.0	2.90	0	245	136	[24]
Oxy-fuel	SNG (CO_2)	Tuyeres & upper	300	0	399	113	270&205	2000	811	0	1143	12.0	2.32	63	216	130	[33]

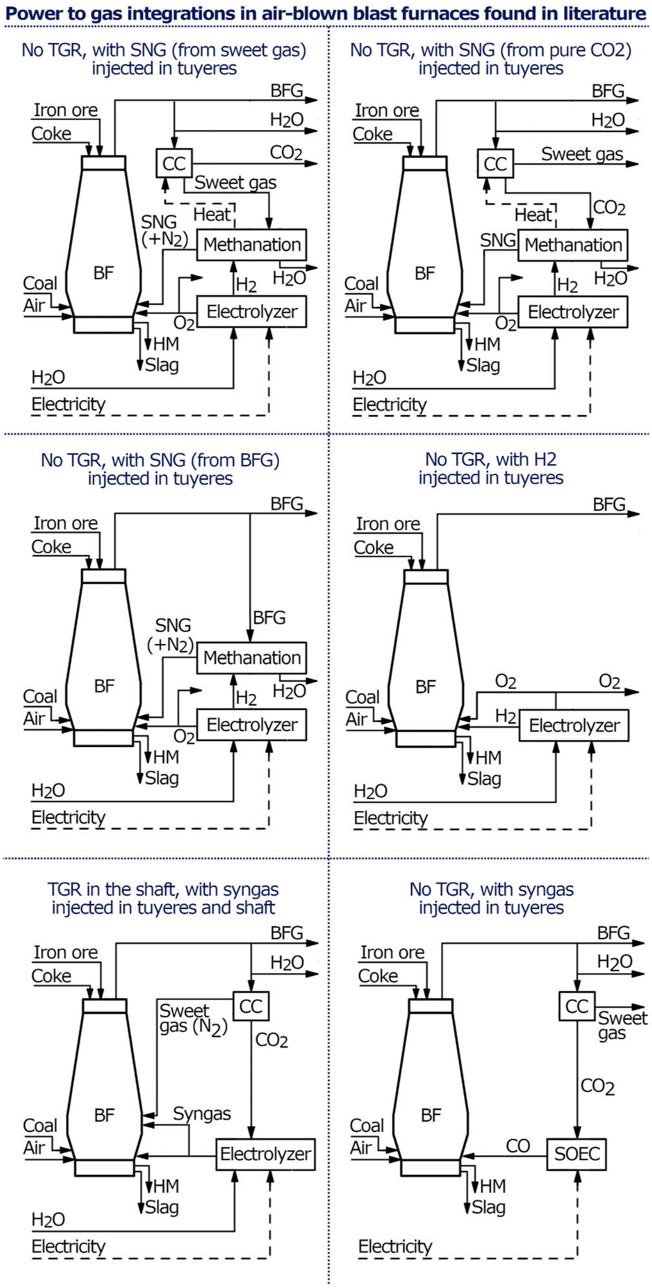

Fig. 3. Process flow diagrams of power to gas integrations in air-blown blast furnaces that have been studied in literature. The left column corresponds to the no recommended configurations because of the recirculation of large amounts of N_2 into the furnace.

sweet BFG methanation, they injected 140 kg_{SNG}/t_{HM} at 900 °C, obtaining a total coal consumption of 541 kg_{Coal}/t_{HM} and emitting 1210 kg_{CO2}/t_{HM} in the blast furnace, see Table 5.

- No TGR, with SNG (from BFG) injected in tuyeres: As stated above, Bailera et al. [26] also analysed this specific configuration, obtaining a total coal consumption of 526 kg_{Coal}/t_{HM} and emitting 1190 kg_{CO2}/t_{HM}.
- TGR in the shaft, with syngas injected in tuyeres and shaft: Hu et al. [30] assessed the opportunities to reduce CO_2 emissions from a conventional blast furnace by means of carbon capture, TGR (shaft injection) and syngas production with a SOEC electrolyser (tuyeres and shaft injection). They studied different cases, varying the proportion of BFG treated in CO_2 capture (from 85 to 100 %), the TGR ratio (from 0 to 15 %), and the H_2/CO selectivity of the SOEC (from 0 to 60 %). The optimum configuration to minimise CO_2 emissions from the BF was for a 100 % BFG capture, a 15 % of TGR ratio and a 60 % of SOEC selectivity. They obtained 1129 kg_{CO2}/t_{HM} of CO_2 emissions in the blast furnace, of which up to 216.2 kg_{CO2}/t_{HM} can be sent to storage.

The other three studied configurations, which not recirculate N_2 into the furnace, are:

- No TGR, with SNG (from pure CO_2) injected in tuyeres: Perpiñán et al. [20] explored a power to SNG integration (CO_2 methanation) in a conventional BF without TGR. They focused on the modelling of the complete iron and steel plant (including sintering, coke oven, power plant, etc.) and the influence of the SNG injection temperature, providing some Sankey diagrams (carbon mole flow, $kg_{CO2\text{-}eq}/t_{HM}$; energy flow, MJ/t_{HM}). Additionally, they performed a pinch analysis for the heat integration of the methanation exothermic heat and the amines endothermic heat demand, resulting in full coverage of the amine steam demand. An injection of 53.6 kg_{SNG}/t_{HM} at 700 °C resulted in total coal consumption of 530.8 kg_{Coal}/t_{HM} and total BF emissions of 1187 kg_{CO2}/t_{HM}. Perpiñán et al. [20] also obtained specific carbon avoidance costs of 283 €/t_{CO2} and 52 €/t_{HM}. Bailera et al. [26] also studied this configuration, injecting the SNG at 900 °C and studying the replacement of coke or coal, achieving a total coal consumption of 500 kg_{Coal}/t_{HM} and emitting 1100 kg_{CO2}/t_{HM}.
- No TGR, with H_2 injected in tuyeres: Yilmaz et al. [27] assessed the influence of hydrogen injection in a conventional blast furnace, using an alkaline electrolyser. They injected 27.5 kg_{H2}/t_{HM} at 1200 °C, emitting 1063 kg_{CO2}/t_{HM}. However, the increase in energy consumption derived from hydrogen preheating led to an energy deficit of 109.7 MJ/t_{HM}. Kim et al. [28] analysed a conventional blast furnace with hydrogen injection from a SOEC electrolyser. They performed a techno-economic analysis, concluding that the optimum injection rate was 20 kg_{H2}/t_{HM}, leading to a specific blast furnace emission of 1182 kg_{CO2}/t_{HM}. Production costs of 8.8 US\$/kg_{H2} are calculated for the year 2021 but are expected to decrease to 1.4–4.0 US\$/kg_{H2} by 2050. Bailera et al. [26] injected preheated hydrogen in the tuyeres (33.4 kg_{H2}/t_{HM} at 900 °C), emitting 1060 kg_{CO2}/t_{HM}. Among the four configurations studied by Bailera et al. [26] (CO_2 methanation, sweet BFG methanation, BFG methanation, and H_2) the H_2 configuration was the less contaminant one, but had a higher energy penalty than other SNG configurations, due to a larger electrolyser, see Table 5.
- No TGR, with syngas injected in tuyeres: Suzuki et al. [6] evaluated a power to syngas system integrated with a conventional blast furnace through the iACRES system (Active Carbon Recycling Energy System in ironmaking). Three different case studies were analysed: (i) SOEC with CCS, (ii) SOEC without CCS and (iii) reverse water-gas shift (RWGS) reactor with CCS. The heat and electricity source of the iACRES system is a high-temperature gas-cooled reactor. They concluded that the second case study was the one with lower emissions in the blast furnace, with 1238 kg_{CO2}/t_{HM}, injecting up to 140 kg_{Syngas}/t_{HM}, see Table 5. Hayashi et al. [29] studied the injection of syngas in a conventional blast furnace with two different syngas production systems: SOEC system, and RWGS with H_2 produced by the iodine-sulphur system. A high-temperature gas-cooled reactor was used in both cases as an energy source. They concluded that the latter system obtained greater CO_2 emission reduction, due to the excess H_2 not consumed in the RWGS that was used as a reducing agent in the BF. However, the former system (SOEC system) was able to obtain a higher CO_2 emission reduction per unit of heat, 5 kg_{CO2}/MJ_{th}, compared with that of the first system (9 kg_{CO2}/MJ_{th}).

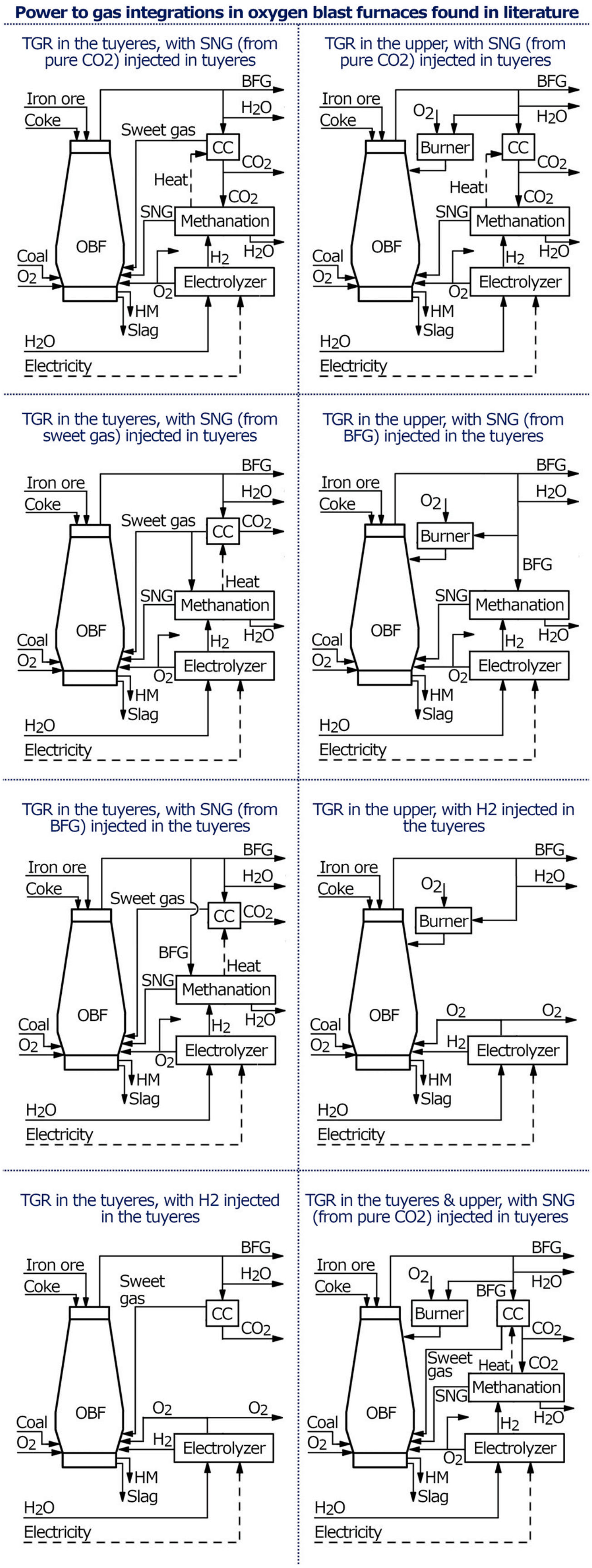

Fig. 4. Process flow diagrams of power to gas integrations in oxygen blast furnaces that have been studied in literature.

4.2. Power to gas integrations in oxygen blast furnaces

Eight power to gas configurations were studied in literature for oxygen blast furnaces (Fig. 4). This represents only the 7 % of the whole outline for the oxy-fuel regime (120 configurations). The work done by each researcher on the corresponding integrations is:

- TGR in the tuyeres, with SNG (from pure CO_2) injected in tuyeres: Bailera et al. revisited the Rist diagram [31], considering multiple injectants, and analysing with great detail for the first time the OBF-PtG integration under the operating diagram methodology. They provided six full data sets of different blast furnaces operations, stating temperatures, compositions and heats of the most relevant operating parameters. Bailera et al. completed this work by extending the operating line [35], to include shaft and preheating injections, and non-continuous oxidation profiles (presence of H_2O and CO_2 in the injected gases). Bailera et al. [26] studied four configurations within the oxygen blast furnace with top gas recycling (tuyeres), including SNG production with CO_2 methanation, sweet BFG methanation, BFG methanation, and H_2 production as a reducing agent. They obtained similar results in the four configurations. For the case of pure CO_2 methanation, they injected 62 kg_{SNG}/t_{HM} at 900 °C, obtaining a total coal consumption of 432 kg_{Coal}/t_{HM} and emitting 925 kg_{CO2}/t_{HM} in the blast furnace, see Table 5.

- TGR in the tuyeres, with SNG (from sweet gas) injected in tuyeres: As stated above, Bailera et al. [26] also analysed this specific configuration, obtaining a total coal consumption of 427 kg_{Coal}/t_{HM} and emitting 925 kg_{CO2}/t_{HM}. This configuration allows for 490 kg_{CO2}/t_{HM} to be sent to storage.
- TGR in the tuyeres, with SNG (from BFG) injected in the tuyeres: A first approach to an oxygen blast furnace-power to gas integration was developed by Perpiñán et al. [25], by using overall energy and mass balances. They considered BFG methanation and recirculation of BFG (tuyeres) without carbon capture. However, this study did not consider the adiabatic flame temperature and the endothermic effect of injecting CO_2 in the tuyeres, resulting in large amounts of BFG recirculated but low emission reductions, see Table 5. Perpiñán et al. [25] also studied BFG methanation with the coke oven gas as a hydrogen source, eliminating the need for an electrolyser. They obtained similar environmental results but great reductions in the energy penalty (from 34 to 4.9 MJ/kg_{CO2}). Bailera et al. [26] also studied this configuration, injecting the SNG at 900 °C and studying the replacement of coke or coal, achieving a total coal consumption of 427 kg_{Coal}/t_{HM} and emitting 910 kg_{CO2}/t_{HM}.
- TGR in the tuyeres, with H_2 injected in the tuyeres: Bailera et al. [26] injected preheated hydrogen in the tuyeres (33.4 kg_{H2}/t_{HM} at 900 °C), emitting 905 kg_{CO2}/t_{HM}, see Table 5.
- TGR in the upper, with SNG (from pure CO_2) injected in tuyeres: Perpiñán et al. [32] studied the influence of the oxygen injection (enrichment, %; temperature °C), on an advanced oxygen blast furnace when integrating a power to SNG system (CO_2 methanation). They concluded that higher enrichments and higher oxygen temperature (up to 1200 °C) led to an increase in the amount of SNG injected (191.5 kg_{SNG}/t_{HM}), which led to lower coal consumption and lower CO_2 emissions, see Table 5. With this configuration, Perpiñán concluded that the oxygen by-produced in the electrolyser could supply the oxygen demand, eliminating the need for the air separation unit. Specific costs of 352 €/t_{CO2} and 233 €/t_{HM} were achieved.
- TGR in the upper, with SNG (from BFG) injected in the tuyeres: Perpiñán et al. [24] performed a sensitivity analysis on an advanced oxygen blast furnace (upper recycling) by varying the H_2:CO_2 ratio of the BFG methanation stage. They studied from a ratio of 2.5 (insufficient H_2, direct CO_2 injection in the BF), through a ratio of 4 (SNG

with 95 % CH_4) to an infinite ratio (pure H_2 injection). For the case of SNG injection, the blast furnace emitted 747 kg_{CO2}/t_{HM}, see Table 5.

- TGR in the upper, with H_2 injected in the tuyeres: As stated above, Perpiñán et al. [24] also analysed this specific configuration, obtaining a total coal consumption of 408 kg_{Coal}/t_{HM} and emitting 833 kg_{CO2}/t_{HM}. Similar results between SNG injection and H_2 injection were obtained, with better environmental results for the former, and improved economic results for the latter, see Table 5.
- TGR in the tuyeres & upper, with SNG (from pure CO_2) injected in tuyeres: Power to SNG integration (CO_2 methanation) in an advanced oxygen blast furnace was studied by Perpiñán et al. [33], analysing the influence of the TGR in this system. In this configuration, the preheating gas mass flow rate (upper recycling) was conditioned by the top gas temperature (150 °C), and a carbon capture stage fed the methanation stage while producing the top gas recycling (tuyeres), so no geological storage was needed. They injected simultaneously 299.9 kg_{Coke}/t_{HM}, 113 kg_{SNG}/t_{HM}, 207 kg_{TGR}/t_{HM} (tuyeres) and 205 $kg_{PreheatingGas}/t_{HM}$ (upper) in the blast furnace, achieving a total CO_2 emission in the BF of 811 kg_{CO2}/t_{HM}.

5. Discussion and comparison of the different power to gas integrations

In this section, the 14 power to gas integrations found in literature (i.e., those summarized in the previous section) are compared using the 14 key performance indicators of Table 2. In order to provide a fair comparison, reference cases for the conventional blast furnace and the oxygen blast furnace with TGR are also included in the comparison.

The first aspect to discuss is the consumption of fuel and reducing agents in the blast furnace. This includes KPI01 (coke), KPI02 (pulverized coal), KPI03 (total coal), KPI04 (synthetic reducing agent: SNG, H_2 or syngas) and KPI05 (top gas recycling), which are presented in Fig. 5. The total coal consumption is 18 % lower in average for oxygen blast furnaces than for air-blown furnaces. Moreover, the total coal consumption decreases more sharply for upper recycling configurations, in comparison with tuyere recycling, thanks to the higher amount of synthetic gas that can be injected (69–202 kg/t_{HM}, instead of 22–63 kg/t_{HM}). The configuration that reaches the lower total coal consumption, 370 kg/t_{HM}, is the advanced oxygen blast furnace with SNG injection, from either CO_2 methanation or BFG methanation.

The adiabatic flame temperature (KPI06) is a technical limitation that influences the amount of reducing agent that can be injected through the tuyeres. These reducing agents decrease the adiabatic flame temperature, which should be above 2000 °C. Other injections such as shaft or upper does not influence this parameter, but are affected by other parameters like the thermal reserve zone or the volumetric flow rate through the blast furnace. Most of the studied reviewed considered this limitation, keeping this temperature between 2000 °C and 2100 °C. Only a few studies, especially those that are a first approach, did not consider this limitation, see Table 5. However further research is needed in this regard, due to the lack of studies assessing this issue.

Regarding the environmental performance, Fig. 6 presents the total BF's CO_2 emissions (KPI07) and the pure stream of CO_2 that can be sent to geological storage (KPI08, see Fig. 1). The most significant CO_2 savings in air-blown blast furnaces reach 1060–1100 kg_{CO2}/t_{HM}, which take place when injecting hydrogen or synthetic natural gas (from CO_2 methanation). This is quite limited since specific emissions remain always above 1000 kg_{CO2}/t_{HM}. Further CO_2 reductions are found for oxygen blast furnaces. In that sense, if geological storage is not an option, upper recycling with SNG injections provides the best results, 738–747 kg_{CO2}/t_{HM}, as it happened for KPI03 (total coal consumption). If geological storage is an option, examining the net CO_2 emissions becomes viable (CO_2 emissions of the BF minus the pure CO_2 sent to storage). Under this scenario, the best configuration is an oxygen blast furnace with top gas recycling (tuyeres) integrated with the methanation of sweet gas, with specific emissions of 435 kg_{CO2}/t_{HM}. Only those configurations that have a carbon capture stage and do not use the CO_2 for synthetic gas production are able to send pure CO_2 to storage (typically between 215 kg_{CO2}/t_{HM} and 490 kg_{CO2}/t_{HM}).

In terms of energy, Fig. 7 quantifies the energy content of the steel gases that remain unused (KPI09) and the energy penalty of the power to gas integration (KPI10). The energy available in the form of steel gases

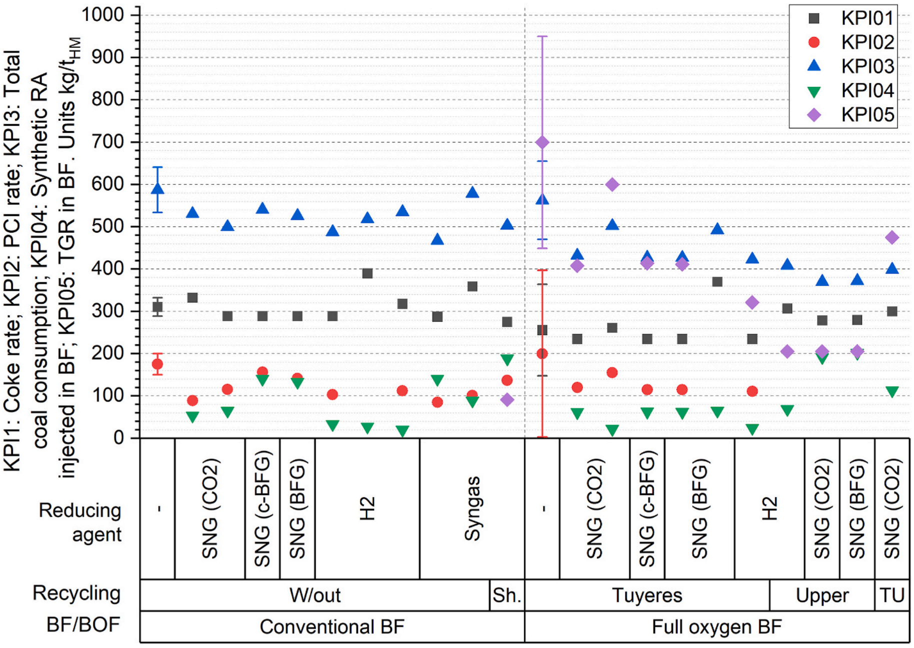

Fig. 5. KPI01: Coke rate (kg_{Coke}/t_{HM}), KPI02: PCI rate (kg_{PCI}/t_{HM}), KPI03: Total coal consumption (PCI + coking coal) (kg_{Coal}/t_{HM}), KPI04: Synthetic RA injected in BF (SNG, H_2, syngas) (kg_{RA}/t_{HM}) and KPI05: TGR in BF (kg_{TGR}/t_{HM}), as a function of the reducing agent production, the BFG recycling and the conventional or oxygen blast furnace. See Table 5. Nomenclature: SNG (CO_2) is synthetic natural gas with CO_2 methanation; SNG (c-BFG) is with clean-BFG methanation; SNG (BFG) is with BFG methanation; W/out is no BFG recycling; Sh is BFG recirculation (TGR) through the shaft; Tuyeres is BFG recirculation (TGR) through the tuyeres; Upper is BFG recirculation (Advanced) through the upper part of the furnace and TU is BFG recirculation through the tuyeres (TGR) and the upper part (Advanced).

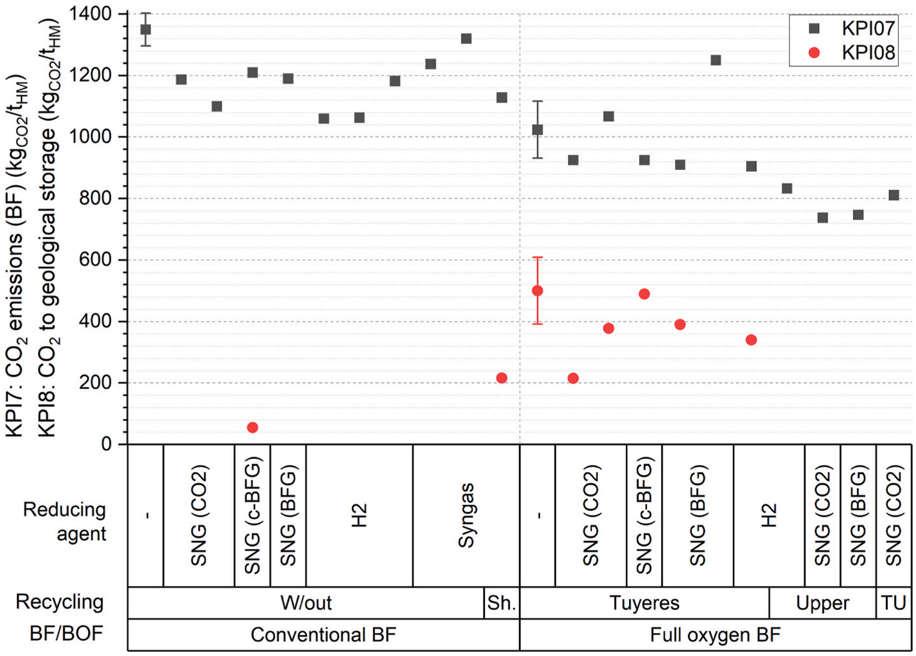

Fig. 6. KPI07: CO_2 emissions (BF) (kg_{CO2}/t_{HM}), KPI08: CO_2 to geological storage (kg_{CO2}/t_{HM}), as a function of the reducing agent production, the BFG recycling and the conventional or oxygen blast furnace. Nomenclature identical to Fig. 5.

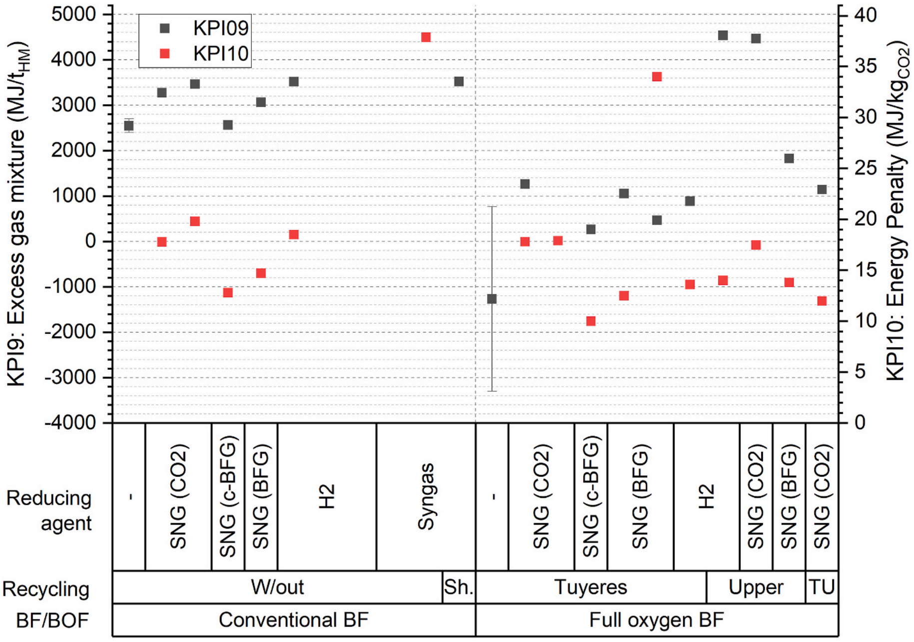

Fig. 7. KPI09: Excess gas mixture (sold or flared) (MJ/t_{HM}), KPI10: Energy Penalty (MJ/kg_{CO2}), as a function of the reducing agent production, the BFG recycling and the conventional or oxygen blast furnace. Nomenclature identical to Fig. 5.

increases by 27 % in average for air-blown blast furnaces because the synthetic reducing agents are not fully consumed in the furnace (the CO and H_2 utilization ratios are in the range from 0.25 to 0.55). This means that part of the synthetic gas from power to gas processes is just flared or sold to nearby industries. Contrarily, oxygen blast furnaces with top gas recycling often have issues with downstream energy supply because large amounts of BFG are recirculated, leading to insufficient steel gases diverted to other processes of the plant [36]. Nevertheless, this problem is solved when integrating power to gas thanks to the addition of energy provided by the electrolyser, thus being able to supply all downstream energy needs. The configurations with lower excess gases (i.e., less wasted energy), but still self-sufficient, are those with TGR in the tuyeres and SNG production. The excess energy in the form of steel gases ranges from 267 MJ/t_{HM} to 4542 MJ/t_{HM} in these oxygen blast furnaces.

The energy penalty of most power to gas integrations ranges between 10 MJ/t_{HM} and 20 MJ/t_{HM}, whether it is an air-blown or oxygen blast furnace (Fig. 7). On average, the energy penalty in oxygen blast furnaces is slightly lower, compared with that of air-blown blast furnaces. When focusing on the SNG (from CO_2 methanation) injection in oxygen blast furnaces, similar energy penalties are found for tuyeres recycling and upper recycling (18 MJ/kg_{CO2}), but it greatly decreases if both tuyere and upper recycling injections are used simultaneously (12 MJ/kg_{CO2}).

The power to gas configuration with lower energy penalty is SNG injection (from sweet gas methanation) independently of the combustion regime (air-blown or oxygen). This is thanks to the lower electrolyser requirement per kg of synthetic gas injected, as some H_2 is already contained in the BFG.

The energy penalty is highly related with the specific electrolyser size required for each PtG integration (KPI11), which is shown in Fig. 8. These values are given in MW/(t_{HM}/h) for illustration purposes, being scalable to any BF size (typical hot metal production is around 320 t_{HM}/h). On average, conventional blast furnaces have electrolyser sizes between 0.2 MW/(t_{HM}/h) and 2.2 MW/(t_{HM}/h), while for oxygen blast furnaces they range between 1.0 MW/(t_{HM}/h) and 4.0 MW/(t_{HM}/h). It must be noted that larger electrolysers do not necessarily mean higher injections of synthetic gas. In fact, in advanced oxygen BF injecting SNG (from CO_2 methanation), 3.96 MW/(t_{HM}/h) are able to produce 191.5 kg_{SNG}/t_{HM}, but if SNG with BFG methanation is chosen, 3.03 MW/(t_{HM}/h) are able to produce 202 kg_{SNG}/t_{HM}. This is due to the hydrogen content in the BFG, which relieves the electrolyser size. Another important factor not directly related to the electrolyser size is the CO_2 emitted. For instance, an oxygen blast furnace with sweet gas methanation and top gas recycling (tuyeres) needs only 0.98 MW/(t_{HM}/h) of electrolysis capacity, but it can restrict the emission to the atmosphere to 435 kg_{CO2}/t_{HM} (with other 490 kg_{CO2}/t_{HM} sent to storage).

One of the advantages of integrating power to gas is the availability of O_2 coming from the water electrolysis, which can replace the oxygen produced in the ASU in the ironmaking plant (KPI12). This drops to cero in most cases, especially in air-blown blast furnaces, given their lower O_2 demand (Fig. 8). For oxygen blast furnaces, the configurations that implement TGR in tuyeres still need an ASU although smaller than in the case without PtG (62–250 kg_{O2}/t_{HM} instead of 250–350 kg_{O2}/t_{HM}), while the configurations with upper injection do not need one. This is due to the higher synthetic gas production in the latter cases, which leads to higher oxygen availability.

Regarding the costs of implementing power to gas in the blast furnace ironmaking, only 5 of the 14 reviewed studies assessed the CO_2 avoidance cost (€/t_{CO2}; KPI13), and the specific implementation cost (€/t_{HM}; KPI14) (Fig. 9). Furthermore, only one study assessed the economic costs of power to gas in air-blown blast furnaces, resulting in 283 €/t_{CO2} and 52 €/t_{HM}, for SNG injection with CO_2 methanation. The same configuration was studied for an advanced oxygen blast furnace, resulting in higher costs (352 €/t_{CO2} and 233 €/t_{HM}); but if combined with TGR (upper and tuyeres), significant reductions can be found in the CO_2 avoidance cost (216 €/t_{CO2}), and a moderate increase in the specific implementation cost (130 €/t_{HM}). These results are in line with the expectations, since higher electrolyser sizes means higher costs (in both €/t_{CO2} and €/t_{HM}), and higher CO_2 avoided means lower CO_2 avoidance cost (€/t_{CO2}). Other configurations show cost results that range in between, such as H_2 injection or SNG injection (from BFG methanation).

For comparison purposes, only one synthetic gas production configuration, SNG with CO_2 methanation, was assessed through three different BFG recirculation configurations, tuyeres, upper and both. The configuration with lower fossil fuel consumption is the one with upper recycling, as it is the one with higher synthetic gas injection. However, the configuration with lower CO_2 emissions is the one with tuyeres recycling, as part of the emissions are sent to storage. The latter is also the one with a smaller electrolyser, which allows for less purchased electricity and therefore lower costs, if compared with upper and both injections.

In summary, for air-blown blast furnaces, direct H_2 injection is the most promising option, followed by SNG from CO_2 methanation, due to its lower CO_2 emissions and similar energy penalty and electrolyser size. For oxygen blast furnaces, if geological storage is not available, the most viable configuration is SNG injection (from BFG methanation) and upper recycling of top gas (advanced OBF), as this option has the lowest fossil fuel consumption and blast furnace emissions, with moderate energy penalty and costs. If geological storage is available, the most attractive solution is SNG (from sweet gas methanation) and top gas recycling in tuyeres, thanks to the ultra-low CO_2 emissions to the atmosphere (435 kg_{CO2}/t_{HM}) and excess gas mixture available, and the moderate energy penalty and electrolyser size (Table 6).

6. Future trends on integrating power to gas with blast furnace ironmaking

Future research should focus on the configurations shown in Table 6, but also on their modifications. For instance, the performance of oxygen

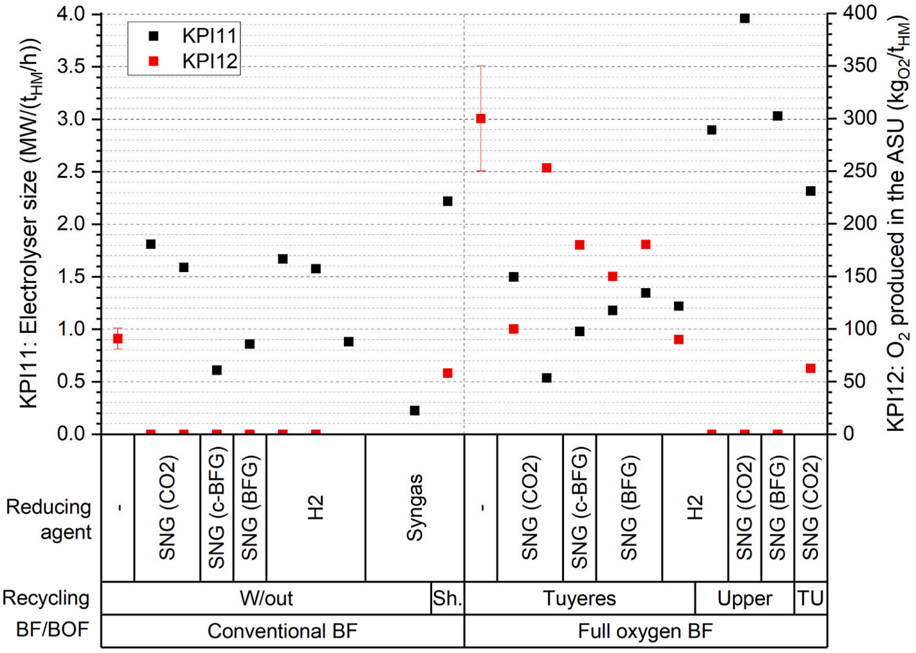

Fig. 8. KPI11: Electrolyser size (MW/(t_{HM}/h)), KPI12: O_2 produced in the ASU (kg_{O2}/t_{HM}), as a function of the reducing agent production, the BFG recycling and the conventional or oxygen blast furnace. Nomenclature identical to Fig. 5.

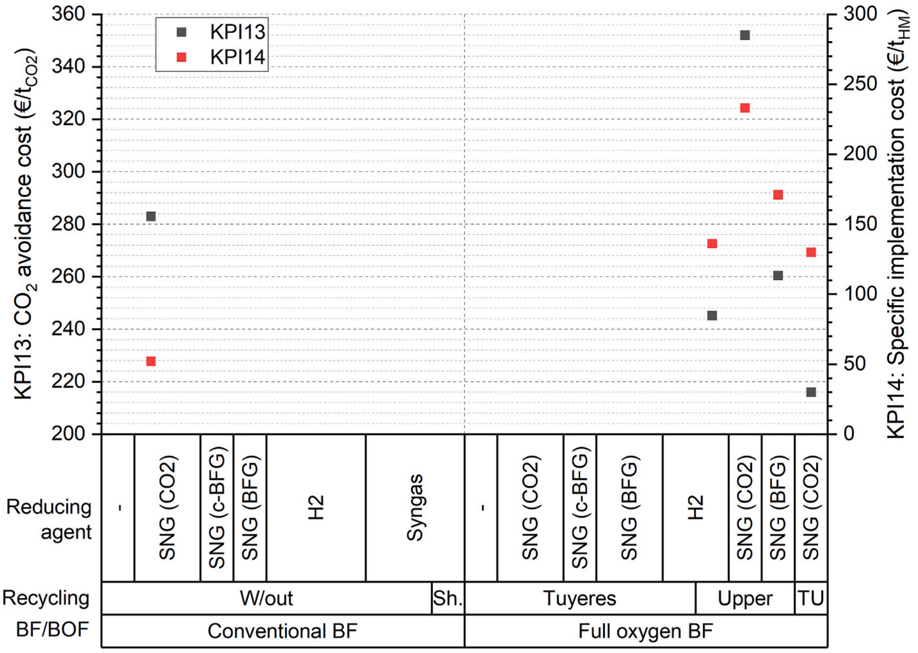

Fig. 9. KPI13: CO_2 avoidance cost (€/t_{CO2}), KPI14: Specific implementation cost (€/t_{HM}), as a function of the reducing agent production, the BFG recycling and the conventional or oxygen blast furnace. Nomenclature identical to Fig. 5.

Table 6
Most feasible configurations based on the articles found in literature for PtG implementation in blast furnace ironmaking.

	Reducing agent	H_2 production	Recycling
Conventional BF	H_2 (tuyeres)	PEM	No
Oxy-BF with CO2 storage	SNG from sweet BFG methanation (tuyeres)	PEM	Top gas recycling (Tuyeres)
Oxy-BF without CO2 storage	SNG from BFG methanation (tuyeres)	PEM	Upper injection (Advanced)

blast furnaces might be improved if the synthetic gas is injected not only in the tuyeres but also in the shaft. The possibility of recycling top gas through the shaft should be analysed too. Moreover, the ratio between the amount of top gas recycling and the amount of SNG injection is worth to be studied in detail. Alternative methods for H_2/CO production, based on SOEC (CO_2 electrolysis) or reverse water gas systems might lead to lower energy consumptions and costs. Besides, advance OBF based on upper recycling seems promising in terms of CO_2 avoidance.

Based on the results and discussion shown in previous sections, authors propose a novel configuration with the following characteristics (Fig. 10):

- Oxygen combustion regime: An oxygen blast furnace allows for larger injections of reducing gases, thanks to the higher temperatures in the tuyeres.
- Top gas recycled in the upper part: This technique regulates the BFG temperature at the top to avoid condensation. It is typically required

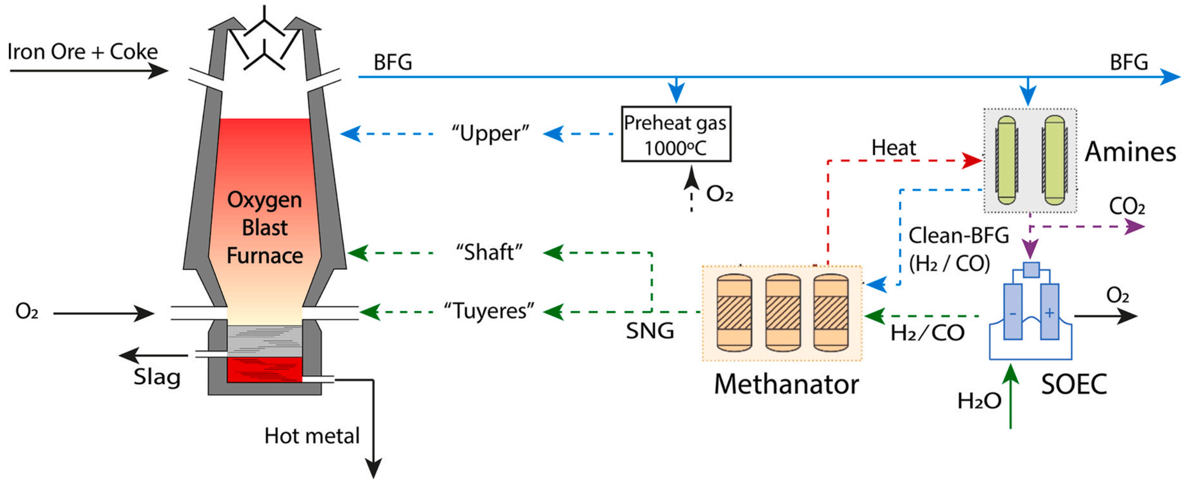

Fig. 10. Process flow diagram proposed by the authors for a novel PtG-ironmaking integration.

when there is no recycling at the tuyeres. In this novel configuration, recirculation at the tuyeres is not included in order to not diminish the flame temperature.

- CO_2 electrolysis as the source for H_2 and CO: This kind of SOEC electrolyser provides lower electricity consumptions, and therefore lower costs.
- Methanation stage for SNG production: An isothermal methanation stage is included to avoid the injection of unreacted CO_2 coming from the SOEC. In addition, sweet gas from amine scrubbing could be used in methanation to adjust stoichiometric ratios and decrease the electrolyser size.
- Amine scrubbing for CO_2 capture: Carbon capture is needed to derive the CO_2 to the SOEC (or storage). The carbon capture stage should be amines, as the heat for amine regeneration can be supplied by the methanation stage. The decision of sending the CO_2 to storage or the SOEC electrolyser depends on two parameters: (i) the availability of storage and (ii) the coverage of the downstream thermal energy needs, as sending CO_2 to the SOEC implies less sweet gas used in methanation, and therefore, more availability for downstream processes. The excess gases should be as close to zero as possible but never below it.
- SNG injected in both tuyeres and shaft: Distributing the gas injection among the tuyeres and the shaft allows increasing the amount of SNG injected, since shaft injections do not decrease the adiabatic flame temperature.
- Pulverized coal replacement: replacing the pulverized coal injection allows for larger SNG injections.

7. Conclusions

In summary, this study comprehensively outlined potential power-to-gas integrations in blast furnace ironmaking, evaluating and comparing relevant literature. Employing a systematic review methodology, 14 key performance indicators (KPIs) were established for comparison, encompassing various aspects such as coke rate, synthetic reducing agent rate, CO2 emissions, costs, and more.

The delineation of potential integrations considered (i) the combustion regime, (ii) the top gas recirculation, (iii) the renewable gas produced, and (iv) the location of the injection of the renewable gas, resulting in 240 possibilities, of which only 14 were studied in literature. Notably, not all configurations are recommended, especially those involving substantial N_2 or CO_2 recycling.

Examining literature, 6 studies were found on power-to-gas integration for air-blown blast furnaces and 8 for oxygen blast furnaces. Oxygen blast furnaces demonstrated an 18 % lower total coal consumption compared to air-blown furnaces, with upper recycling configurations further reducing consumption. While power-to-gas systems had limited impact on CO2 emissions for air-blown furnaces, significant reductions were observed for oxygen blast furnaces, especially when underground storage was available.

The surplus steel gases' energy content increased by 27 % in air-blown blast furnaces using power-to-gas. Oxygen blast furnace configurations combining tuyere gas recycling and power-to-gas minimized wasted energy, with excess energy ranging from 267 MJ/t_{HM} to 4542 MJ/t_{HM}.

Electrolyser sizes depended on BFG's H_2 content and on the configuration analysed, in the range of 0.2 and 2.2 $MW/(t_{HM}/h)$. Additionally, the integration of electrolysis eliminated the need for an air separation unit in many cases, enhancing efficiency.

In terms of cost, only 5 out of 14 studies performed this analysis, with costs. Configurations with SNG injection using CO_2 methanation had lower costs for air-blown (283 $€/t_{CO2}$) than for advanced oxygen blast furnaces (352 $€/t_{CO2}$). Combined TGR in upper and tuyeres lead to important reductions in CO_2 avoidance cost (216 $€/t_{CO2}$).

Depending on the approach (air-blown BF, oxygen BF, or oxygen BF with CO_2 storage), the most feasible configurations among the already studied in literature are:

- Air-blown blast furnace: H_2 as a reducing agent (injected through the tuyeres), produced with a PEM electrolyser, and without top gas recycling. The CO_2 emissions to atmosphere are 1060 kg_{CO2}/t_{HM}.
- Oxygen blast furnace: SNG from BFG methanation as a reducing agent (injected through the tuyeres), produced with a PEM electrolyser and with top gas recycling in the upper part (advanced oxygen blast furnace). The CO_2 emissions to atmosphere are 747 kg_{CO2}/t_{HM}.
- Oxygen blast furnace combined with geological storage: SNG from sweet gas methanation as a reducing agent (injected through the tuyeres), produced with a PEM electrolyser and with top gas recycling in the tuyeres. The CO_2 emissions to atmosphere are 435 kg_{CO2}/t_{HM}. The CO_2 emissions sent to the storage are 490 kg_{CO2}/t_{HM}.

Future studies should validate successful technologies, particularly advanced oxygen blast furnaces with upper recycling. Addressing the current high expenses of these systems is crucial, and prioritizing efforts to reduce the energy penalty associated with green hydrogen production is essential.

Author contributions

Conceptualization, J.P., M.B. and B.P.; methodology, J.P., M.B. and B.P.; formal analysis, J.P.; writing—original draft preparation, J.P. and M.B.; writing—review and editing, M.B. and B.P.; visualization, J.P. and M.B.; supervision, M.B., and B.P.; project administration and funding acquisition, M.B., and B.P. All authors have read and agreed to the published version of the manuscript.

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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References

[1] International energy agency, iron and steel technology roadmap. https://www.iea.org/reports/iron-and-steel-technology-roadmap. [Accessed 26 April 2022].
[2] Cores A, et al. Iron ore sintering. Part 3: automatic and control systems. DYNA May 2015;82(190):227–36. https://doi.org/10.15446/dyna.v82n190.44054.
[3] Remus R, Aguado-Monsonet Ma, Roudier S, Sancho LD. Best available techniques (BAT) reference document for iron and steel production. 2013. https://doi.org/10.2791/98516.
[4] Piringer H, Bucher P, Wallimann R. Sustainable lime burning technology with shaft kilns. ZKG Cem. Lime Gypsum 2021;(6).
[5] Babich A, Senk D, Gudenau H, Mavrommatis KT. Ironmaking textbook. RWTH Aachen University; 2008.
[6] Suzuki K, Hayashi K, Kuribara K, Nakagaki T, Kasahara S. Quantitative evaluation of CO2 emission reduction of active carbon recycling energy system for ironmaking by modeling with aspen plus. ISIJ Int 2015;55(2):340–7. https://doi.org/10.2355/isijinternational.55.340.

[7] Zhang W, Dai J, Li C, Yu X, Xue Z, Saxén H. A review on explorations of the oxygen blast furnace process. Steel Res Int 2021;92(1). https://doi.org/10.1002/srin.202000326.
[8] Bailera M, Lisbona P, Peña B, Romeo LM. A review on CO2 mitigation in the Iron and Steel industry through Power to X processes. J CO2 Util 2021;46(November 2020):101456. https://doi.org/10.1016/j.jcou.2021.101456.
[9] Rosenfeld DC, Böhm H, Lindorfer J, Lehner M. 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 2020;147:1511–24. https://doi.org/10.1016/j.renene.2019.09.053.
[10] Medved AR, Lehner M, Rosenfeld DC, Lindorfer J, Rechberger K. Enrichment of integrated steel plant process gases with implementation of renewable energy Integration of power-To-gas and biomass gasification system in steel production. Johnson Matthey Technol. Rev. 2021;65(3):453–65. https://doi.org/10.1595/205651321x16161444481140.
[11] Kato Y. Utilization of HTGR on active carbon recycling energy system. Nucl Eng Des 2014;271:79–83. https://doi.org/10.1016/j.nucengdes.2013.11.014.
[12] Kato Y, et al. Performance analysis of active carbon recycling energy system. Prog Nucl Energy 2011;53(7):1017–21. https://doi.org/10.1016/j.pnucene.2011.04.024.
[13] Dipu AL, Ryu J, Kato Y. Carbon dioxide electrolysis for a carbon-recycling iron-making system. ISIJ Int 2012;52(8):1427–32. https://doi.org/10.2355/isijinternational.52.1427.
[14] Dipu AL, Ujisawa Y, Ryu J, Kato Y. Carbon dioxide reduction in a tubular solid oxide electrolysis cell for a carbon recycling energy system. Nucl Eng Des 2014;271:30–5. https://doi.org/10.1016/j.nucengdes.2013.11.004.
[15] Hisashige S, Nakagaki T, Yamamoto T. CO2 emission reduction and exergy analysis of smart steelmaking system adaptive for flexible operating conditions. ISIJ Int 2019;59(4):598–606. https://doi.org/10.2355/isijinternational.ISIJINT-2018-355.
[16] Zhao J, Zuo H, Wang Y, Wang J, Xue Q. Review of green and low-carbon ironmaking technology. Ironmak Steelmak 2020;47(3):296–306. https://doi.org/10.1080/03019233.2019.1639029.
[17] Lan C, Hao Y, Shao J, Zhang S, Liu R, Lyu Q. Effect of H2 on blast furnace ironmaking: a review. Metals 2022;12(11). https://doi.org/10.3390/met12111864.
[18] Chen Y, Zuo H. Review of hydrogen-rich ironmaking technology in blast furnace. Ironmak Steelmak 2021;48(6):749–68. https://doi.org/10.1080/03019233.2021.1909992.
[19] Page MJ, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372. https://doi.org/10.1136/bmj.n71.
[20] Perpiñán J, Bailera M, Peña B, Romeo LM, Eveloy V. Technical and economic assessment of iron and steelmaking decarbonization via power to gas and amine scrubbing. Energy 2023;276. https://doi.org/10.1016/j.energy.2023.127616.
[21] Peacey JG, Davbenport WG. The Iron Blast Furnace. Theory and Practice 1979: 1979. ISBN 0-08-023258-2.
[22] Wu J, Wang R, Pu G, Qi H. Integrated assessment of exergy, energy and carbon dioxide emissions in an iron and steel industrial network. Appl Energy 2016;183:430–44. https://doi.org/10.1016/j.apenergy.2016.08.192.
[23] European Commission. ULCOS top gas recycling blast furnace process (ULCOS TGRBF). Final Report; 2014. https://doi.org/10.2777/59481.
[24] Perpiñán J, Bailera M, Peña B. Full oxygen blast furnace steelmaking: from direct hydrogen injection to methanized BFG injection. Energy Convers Manag 2023. https://doi.org/10.1016/j.enconman.2023.117611.
[25] Perpiñán J, Bailera M, Romeo LM, Peña B, Eveloy V. CO2 recycling in the iron and steel industry via power-to-gas and oxy-fuel combustion. Energies 2021;14(21):7090. https://doi.org/10.3390/en14217090.
[26] Bailera M, Nakagaki T, Kataoka R. Limits on the integration of power to gas with blast furnace ironmaking. Elsevier; Sep. 2022. https://doi.org/10.1016/J.JCLEPRO.2022.134038.
[27] Yilmaz C, Wendelstorf J, Turek T. Modeling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions. J Clean Prod 2017;154:488–501. https://doi.org/10.1016/j.jclepro.2017.03.162.
[28] Kim J, et al. An integrative process of blast furnace and SOEC for hydrogen utilization: techno-economic and environmental impact assessment. Energy Convers Manag 2021;250(August):114922. https://doi.org/10.1016/j.enconman.2021.114922.
[29] Hayashi K, et al. Process evaluation of use of high temperature gas-cooled reactors to an ironmaking system based on active carbon recycling energy system. ISIJ Int 2015;55(2):348–58. https://doi.org/10.2355/isijinternational.55.348.
[30] Hu Y, et al. Opportunities to reduce energy consumption and CO_2 emissions from ironmaking blast furnace using CO_2 electrolysis to CO for carbon recycling. J Clean Prod 2023;389(January):135997. https://doi.org/10.1016/j.jclepro.2023.135997.
[31] Bailera M, Nakagaki T, Kataoka R. Revisiting the Rist diagram for predicting operating conditions in blast furnaces with multiple injections. 2021. https://doi.org/10.12688/openreseurope.14275.1.
[32] Perpiñán J, Bailera M, Peña B, Romeo LM, Eveloy V. High oxygen and SNG injection in blast furnace steelmaking with Power to Gas integration and CO2 recycling. J Clean Prod 2023. https://doi.org/10.1016/j.jclepro.2023.137001.
[33] Perpiñán J, Bailera M, Peña B, Kannan P, Eveloy V, Romeo LM. Power to Gas and Top Gas Recycling integration in an oxygen blast furnace steelmaking industry. 2023. https://doi.org/10.1016/j.jcou.2023.102634.
[34] Danloy G, et al. Ulcos - pilot testing of the low-CO2 Blast Furnace process at the experimental BF in Lulea. Rev. Metall. Cah. D'Informations Tech. 2009;106(1):1–8. https://doi.org/10.1051/metal/2009008.
[35] Bailera M, Nakagaki T, Kataoka R. Extending the operating line methodology to consider shaft and preheating injections in blast furnaces. ISIJ Int 2022;62(12):1–12. https://doi.org/10.2355/isijinternational.ISIJINT-2022-111.
[36] Sahu RK, Roy SK, Sen PK. Applicability of top gas recycle blast furnace with downstream integration and sequestration in an integrated steel plant. Steel Res Int 2015;1(5):502–16. https://doi.org/10.1002/srin.201400196.