TECHNICAL AND ECONOMIC VIABILITY OF GLASSMAKING DECARBONIZATION THROUGH POWER TO GAS AND CARBON CAPTURE

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ABSTRACT

The decarbonisation of energy-intensive industries, such as the glass industry, is a key step to comply with the Paris Agreement. Two different low-carbon integrations based on Power-to-gas are simulated in Aspen Plus v.11. Fossil natural gas is substituted by synthetic natural gas, produced within the bounds of the industry in a methanation reactor, forming a closed loop. This is achieved by combining green H_2 produced in a PEM electrolyzer with a CO_2 stream. Case 1 features a calcium looping (CaL) capture plant as the way of obtaining the CO_2, whereas cases 2 is based on oxy-combustion. In case 2, the furnace is operated with O_2-CO_2 atmosphere, offering a quick solution for existing glassmaking plants to avoid furnace substitution. The scenarios are compared from a techno-economic point of view under three economic scenarios, namely, full electricity purchase, self-production via a photovoltaic plant, and self-production via a wind farm.

1 INTRODUCTION

To curb the rise in global average temperature increase to 1.5 ºC compared to industrial levels, it is required to develop technologies to decarbonize the energy-intensive industries involving high temperature processes, such as the glass industry (4-17 GJ/t_{glass}) (The Paris Agreement, 2015). The required energy is usually provided by combustion of fossil fuels, such as natural gas, making them still associated with high carbon dioxide emissions. Its main subsectors, namely the container and flat glass industry, account for 80% of the global and European glass production, emitting around 81 Mt_{CO2}(Westbroek et al., 2021) and 18 Mt_{CO2} (Zier et al., 2021), respectively. The melting process constitutes the primary energy expenditure in the plant, accounting for approximately 75-85% of total energy consumption and emitting around 75% of total emissions. In the container industry, the best practical limits for the melting process are between 3 – 3.5 GJ/t (Papadogeorgos and Schure, 2019).

Switching fuels poses challenges, requiring adjustments to operating permits and installations, including the incorporation of new burners and control systems. However, despite the challenges, fuel switching presents a greater potential for decarbonization. Potential options include the adoption of electric furnaces or the utilization of gaseous energy carriers. All-electric solutions find application in certain specialized glass manufacturing processes, but their implementation is currently limited to small scales, typically up to 250 t/day. For widespread adoption in high-scale container glass production, especially when incorporating high cullet rates, significant furnace innovation is necessary to address associated challenges. Challenges include the rapid melting of the mixture with high cullet (recycled glass) rates, hindering the formation of a stable layer, and a lack of flexibility in handling variable loads (Conradt, 2019)(Papadogeorgos and Schure, 2019). Additionally, these solutions may not be suitable for all glass types due to limitations related to electrical ion conductivity (Zier et al., 2021).

The possibility of utilizing hydrogen has been investigated. Despite these advancements, numerous challenges persist. These include the need for the development of new burners to adapt furnace operations to the altered combustion conditions, characterized by lower radiation heat transfer and

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volumetric energy content (Furszyfer Del Rio et al., 2022). Additionally, the emitted wavelength may not align optimally with heavy-fuel air flame or natural gas, potentially impacting efficiency (Papadogeorgos and Schure, 2019). It also comes into question if the increased water content in the exhaust gas may create foam, having a negative effect on the glass quality (Zier et al., 2021).

Within this last research line, power-to-methane emerges as an alternative, involving the capture of CO_2 emitted during the melting process, which is then combined with green hydrogen to generate synthetic methane. This approach addresses many of the limitations associated with hydrogen combustion, as it is assumed that composition of the synthetic gas is similar to that of natural gas and can be directly substituted without altering the furnace operation (Papadogeorgos and Schure, 2019). State-of-the-art regarding carbon capture is amine scrubbing. However, it involves important concerns related to degradation, corrosion and toxicity, which have not yet been solved. The Calcium Looping (CaL) capture technology presents advantages such as lower energy penalty, a better exergetic efficiency, versatility, and a cheap, available, non-toxic sorbent.

Another possibility is oxy-combustion. In oxy-fuel combustion, O_2 concentration in the comburent in the oxidizer is increased from 21 vol%O_2 to 100 vol% O_2, which avoids having to heat the unnecessary nitrogen in air and as a consquence fuel usage may decrease. Additionally, the use of oxygen instead of air reduces specific NOx emissions, and creates a reasonably pure CO_2 stream (Papadogeorgos and Schure, 2019), making it possible to get rid of a carbon capture stage. However, the estimated lifetime of an air-combusted melting furnace is 20 years. (Paardekooper, 2018). It is not expected for an industry to replace it for a oxy-fuel furnace before the end of its operation, as it would incur in higher costs. To avoid a premature furnace substitution, an operation with a O_2:CO_2 ratio of 21:79 with a similar mass flow as before is proposed, keeping similar operational conditions to that of the conventional process, offering a quick solution until the furnace is substituted.

This article aims to compare from a techno-economic point of view two different scenarios: power-to-methane with a CaL capture plant and operation with a O_2-CO_2 atmosphere. The different processes of the glassmaking plant, as well as the proposed integrations, are modelled in Aspen Plus v11. The different scenarios are compared in terms of natural gas and electricity consumption, CO_2 emissions, energy penalty, and economic profitability.

2 METHODOLOGY

This work is focused on the container industry, representing 47% of the total glass industry accounted for in the European Emissions Trading system (EU ETS) (Zier et al., 2021). Specifically, the most common melting technology based in fossil natural gas has been considered as reference case (case 0). Two additional case studies based on the Power-to-Gas concept are proposed to reduce fossil natural gas (NG) consumption and CO_2 emissions, and their potential benefit of these variants are assessed regarding reductions of energy penalties or raw material consumption. For comparison purpose, the analysis has been performed in specific units (per ton of glass product, t_{glass}) and afterwards sized to net amounts for a glass plant of medium size (250 t_{glass}/day).

2.1 Case studies

2.1.1. Conventional Glass production process (reference case): The reference case study (Case 0) is represented in Figure 1. A typical scheme of a conventional glass plant is considered, considering its 7 main stages: batch, melting, refining, forming, annealing, surface treatment and inspection. Most of the energy consumption (in the way of NG) takes place in the high temperature processes that occur in the melting, fining and annealing stages, while electricity is consumed to a lesser extent in every stage. Electricity is considered to come from renewable sources, so no indirect CO_2 emissions are considered. Input data for Case 0 can be seen in Table 1. Cullet glass comes from glass that does not meet quality requirements. It can either come from inside the glassmaking process (domestic cullet) or from specific recovery plants (external cullet).

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Table 1: Input data of a container glass production plant (Papadogeorgos and Schure, 2019)

Variable	Units	Case 0	Variable	Units	Case 0
Raw material			*Cullet ratios*		
Silica Sand	kg/t_{glass}	191	Rejected glass	kg/t_{glass}	22
Dolomite	kg/t_{glass}	34	Defective glass	kg/t_{glass}	89
Limestone	kg/t_{glass}	24	*Glass composition*		
Sodium carbonate	kg/t_{glass}	57	SiO_2	%wt	73.26
Sodium sulphate	kg/t_{glass}	2	Na_2O	%wt	12.61
External cullet	kg/t_{glass}	744	CaO	%wt	9.92
Domestic cullet	kg/t_{glass}	111	MgO	%wt	2.55

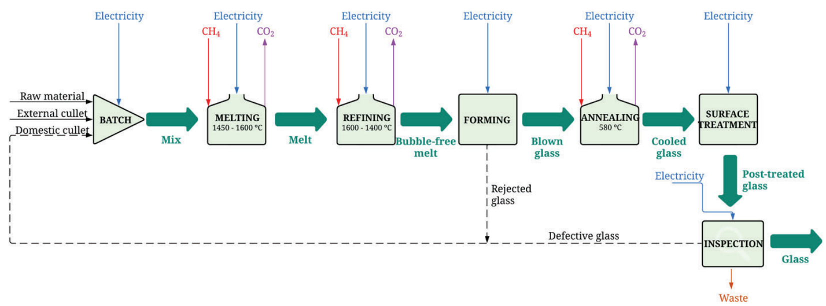

Figure 1: Reference case corresponding to a conventional glass plant (own elaboration)

2.1.2. Low-carbon concepts: The conventional glassmaking plant has been integrated with a power-to-gas (PtG) system in two different configurations (Figure 2). The main additional equipment consists of a PEM (proton-exchange membrane) electrolyzer powered by renewable energy and a catalytic methanation reactor. In case 1, the plant is also equipped with a CaL carbon capture system. Although amine scrubbing is considered state-of-the-art as capture technology in power plants (Perpiñán et al., 2023b), CaL offers integration advantages, as spent lime can be reutilized instead of dolomite or limestone. Synthetic natural gas (SNG) is produced in the methanation system by combining the captured CO_2 from the glassmaking process with the hydrogen from the electrolyzer. The by-produced O_2 is used internally for oxy-combustion in the calciner. The excess O_2 is sold to other industries. Some of the CaO purged in the CaL system is used as raw material for the glassmaking plant, replacing part of the limestone. This strategy involves some benefits, as the equivalent quantities of limestone ($CaCO_3$) do not have to be introduced and decomposed (strongly endothermic reaction), reducing raw material and fuel consumption, and avoiding such process emissions. Furthermore, a Rankine Power plant in which waste heat is recovered from methanation and capture systems is also integrated into the model. Three turbines and four pressure levels have been included (Manzolini et al., 2020).

Case 2 avoids the need of a carbon capture plant using oxy-combustion in a 21-79% O_2/CO_2 atmosphere in the melting and refining furnaces. Water in the flue gases leaving the furnaces is condensed, obtaining a pure CO_2 stream, which is directly rerouted to the methanation reactor. Since not all of it can be introduced into the methanation reactor, the excess, pure, CO_2 stream should be geologically stored or sold to other industries.

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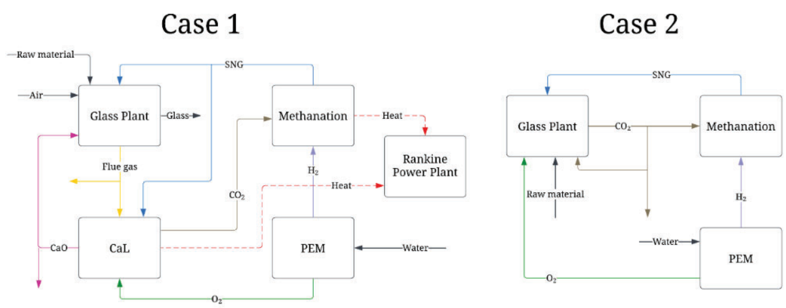

Figure 2: Proposed low-carbon configurations

2.2 Modelling procedure

The reference case study (Case 0), representing a conventional container glass plant, as well as the low-carbon concepts (Cases 1-2), have been modelled and simulated in Aspen Plus v.11, under steady-state conditions. For a more detailed description of the models, see (Barón et al., 2023).

2.2.1. Glassmaking plant model: The stages represented in Figure 1 have been implemented in the Aspen model for the conventional glass plant. The model is initially developed and validated with data from the literature. The composition of outlet glass is identical for Cases 0-2 and keeps constant from the melting furnace up to the plant exit after the inspection stage. Only the main components (SiO_2, Na_2O, CaO and MgO) have been considered, as they roughly summarize 96% of real content. (Madivate, 2005).

After integration with the low-carbon technologies, certain inputs are adapted to keep constant the proper outputs in the different equipment. The mass flow of raw material is maintained in Cases 0 and 2. In case 1, the limestone mass flow is reduced according to the CaO recirculation to obtain the same glass composition. The quantity and composition of the flue gases of the melting furnace differ between cases 0-1 and 2. A stream purely composed of water and CO_2 is obtained in Case 2. Operating conditions in the melting furnace change due to the different input mass flows. However, outlet flue gas temperature after going through the regenerative heat exchanger has been considered the same in all cases.

Melting, fining and annealing furnaces have been modelled as stoichiometric reactors. The required thermal energy in those processes is provided by the complete combustion of either the fossil NG or the SNG generated in the methanation (94.77% CH_4, 3.96% H_2 and 1.27% CO_2, LHV = 49 MJ/kg). The excess air is set to 10% for the combustion in all cases, as it is a typical value in the industry. The decomposition process reactions (Eqs. 1-4) are considered complete (100% conversion) in the melting furnace. The temperatures of melting and fining furnaces have been set to 1600 °C. Typical temperature figures have been assumed for the regenerative heat exchanger. Air is preheated before melting furnace with the outlet flue gases, which reduce their temperature from 1600 °C to 550 °C. Atmospheric pressure has been considered in every stage.

$$Na_2CO_3\ (s) \longrightarrow Na_2O(s) + CO_2\ (g) \qquad \Delta H_{298}=273.3\ kJ/mol \qquad (1)$$
$$CaMg(CO_3)_2\ (s) \longrightarrow CaCO_3\ (s) + CO_2\ (g) + MgO\ (s) \qquad \Delta H_{298}=68.9\ kJ/mol \qquad (2)$$
$$CaCO_3\ (s) \longrightarrow CaO\ (s) + CO_2\ (g) \qquad \Delta H_{298}=473.7\ kJ/mol \qquad (3)$$
$$Na_2SO_4\ (s) \longrightarrow Na_2O\ (s) + SO_3\ (g) \qquad \Delta H_{298}=522.4\ kJ/mol \qquad (4)$$

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2.2.2. Power-to-gas system: The PEM electrolyzer produces hydrogen (0.002 % O_2) and oxygen (0.02% H_2), with 3.8 kW_e/Nm^3 energy consumption. The methanation system consists of two isothermal fixed-bed reactors, reaching higher yields than for adiabatic conditions(Izumiya and Shimada, 2021) (Rönsch et al., 2016). A gas hourly space velocity, GHSV, (eq. 5) of 5000 h^{-1} is considered (Perpiñán et al., 2023a), where $\dot{V}_{gas}$ (m^3/h) represents the hourly volume flow of gas going through the system, and $V_{catalyst}$ (m^3) the volume of the catalyst in the reactors. The main reactions are shown in Eqs. 6-7. The H_2 is compressed and mixed in stoichiometric ratio (4:1) with the CO_2 stream coming from CaL system. The resulting SNG stream is separated from water at 25 °C in a flash separator.

$$GHSV\ [h^{-1}] = \dot{V}_{gas} / V_{catalyst} \tag{5}$$

$$CO_2 + 4H_2 \Leftrightarrow CH_4 + 2H_2O \qquad \Delta H_{298}=-113.6\ kJ/mol \tag{6}$$

$$CO + 3H_2 \Leftrightarrow CH_4 + H_2O \qquad \Delta H_{298}=-485.2\ kJ/mol \tag{7}$$

2.2.3. Calcium-looping capture system: CaL technology is used in Case 1 to capture the CO_2 present in the flue gases that leave the melting furnace. The main equipment of the CaL system are the calciner and the carbonator, which have been modelled in Aspen Plus as stoichiometric reactors with 90% (to CO_2) and 100% conversion, respectively (Sánchez-Biezma et al., 2013) (Ortiz et al., 2017). The exothermic carbonation reaction takes place in the carbonator: the CO_2 contained in the flue gas stream coming from the glass melting furnace reacts with the CaO to produce $CaCO_3$. The resulting limestone ($CaCO_3$) is driven to the calciner to release a CO_2-rich stream. The endothermic decomposition of $CaCO_3$ regenerates the CaO and liberates the CO_2 (ΔH_{298K} = 177.9 kJ/mol). The required thermal energy is provided by the oxy-combustion of a part SNG produced in the PtG system. A CO_2 recirculation loop at the exit of the calciner prevents the appearance of hot spots at the entrance that could damage the process. The amount of CO_2 recirculated is set to obtain 21% O_2 at the entrance of the calciner; emulating air conditions. Oxygen is introduced in stoichiometric quantities and complete combustion is considered. A sorbent purge is usually included to prevent excessive amounts of sintered CaO, formed because of the high temperatures which reduces the efficiency of the CaL system. It has been located before the entrance of the carbonator, with the purpose of easing the CaO transport to the melting furnace.

2.2.4. Power Plant: In case 1, a Rankine cycle with three evaporators, three turbines and four pressure levels is considered for power generation from waste heat recovered from the CaL system and the first methanation reactor. It is noteworthy that the Rankine Power plant works independently from the rest of the system.

2.3 Economic analysis

Three different scenarios have been compared from the economic point of view: electricity purchase, self-consumption through a photovoltaic (PV) plant, and self-consumption through a wind farm (WF). The nominal power of both the PV plant and the wind farm have been sized to cover the electricity consumption needed for the 3 different cases.

The economic analysis has been conducted by using parameters based on September 2022 data. The correlations were obtained from (Barón et al., 2023) Although the glass industry operates under continuous production, service and maintenance stops are also considered, rendering an equivalent of 8000 h of production per year. For the reference case, 77 €/MWh_e electricity cost , 80 €/t_{O2} selling price of oxygen, 90 €/t_{CO2} CO_2 tax, 0,787 €/kg_{NG} natural gas price, and 10 €/t_{CaCO3} limestone price (Ortiz et al., 2019) are considered. Regarding Case 2, excess CO_2 will be stored at transport price (10€/t_{CO2}) (Smith et al., 2021), and the substitution of an existing furnace for an oxy-glass furnace is considered to be 15 M€ (Papadogeorgos and Schure, 2019). A time horizon of 20 years with an annual interest of 4% is assumed. Regarding methanation, in order to calculate the necessary catalyst mass, a GHSV of 5000 h^{-1} has been considered, assuming the bed occupies 60% of the volume of the reactors. As for the PV and wind farms, an initial investment of 620 €/kW and 1325 €/kW with typical utilization factors in Spain of 25% and 43% are considered, respectively(RDL14/2010) (IRENA, 2022).

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2.4 Key Performance Indicators

A total of 15 KPIs are assessed in order to evaluate the obtained results. KPIs 1 to 5 refer to CaL, PtG, Rankine cycle and PEM electrolyzer. KPIs 1 and 2 are the amount of thermal energy necessary in both CaL reactors with respect to the CO_2 captured and the glass produced, respectively. KPI 3 considers the amount of synthetic natural gas produced in the methanation system. KPI 4 amounts the electricity generated in the power plant per glass mass unit, only included in case 1. Finally, KPI 5 takes account of the electricity consumed by the electrolyzer, responsible of the largest part of the consumption. KPI 6 equals the net electricity consumption per glass mass produced, after discounting the electricity generated by the Rankine power plant. KPIs 7 and 8 refer, respectively, to the CO_2 emissions and to the CO_2 stored or sold. KPI 9 refers to the energy penalty incurred. KPIs 10 to 15 focus on the economic assessment. KPI 10 references the 20-year balance of the case, while KPI 11 is CAPEX, 12 incomes and 13 OPEX. KPI 14 represents the carbon abatement cost (see eq. 8) per ton of CO_2 and KPI 15 the specific implementation cost of the PtG system per ton of glass (see eq. 9).

$$\text{Carbon abatement cost } [€/t_{CO2}] = 10^6 * \left(\frac{\text{KPI11}}{n} - \text{KPI12} + \text{KPI13}\right) / \Delta\dot{m}_{CO2} \quad (8)$$

$$\text{Specific implementation cost } [€/t_{glass}] = 10^6 * \left(\frac{\text{KPI16}}{n} - \text{KPI12} + \text{KPI13}\right) / \dot{m}_{glass} \quad (9)$$

where n references the loan amortization period (in this case, 20 years), $\Delta\dot{m}_{CO2}$ the amount of CO_2 avoided yearly (t_{CO2}/y) and $\dot{m}_{glass}$ the annual hot metal production (t_{glass}/y).

3 RESULTS AND DISCUSSION

The technical analysis regarding the advantages and disadvantages of the proposed low-carbon concepts within the context of energy and CO_2 emissions are discussed in Section 3.1. The economic aspect is discussed in Section 3.2.

3.1 Technical comparison of low-carbon concepts

KPIs 1 to 15 are presented in Table 2. It is noteworthy that KPIs 1,2 and 4 only relate to Case 1, as no carbon capture stage has been implemented in Case 2. KPI 3 (SNG production) is different for each case. Case 1 requires the most SNG, since not only the glass furnace is supplied by it, but also the calciner from the calcium looping plant. This is avoided in Case 2, while maintaining a similar SNG flow to the glass furnace as the operation conditions are similar to case 1. Net electricity consumption (KPI 6) is mainly related to the electrolyzer, which is also directly related to SNG production (KPI 3). It is to be noted that, beforehand, it could be argued that the Rankine power plant (KPI 4) introduced in Case 1 might be enough to compensate for the higher electrolyzer consumption (KPI 5). However, it is not enough, and case 1 presents the highest electricity consumption (KPI 6).

Figure 3 plots KPIs 7 (left) and KPIs 6-9 (right). KPIs 7 and 8 reference the CO_2 emissions. With regard to the CO_2 emissions (KPI 7), case 1 presents a 84% reduction while case 2 present a 96% reduction. This is a result of the nature of the inevitable purge of part of the flue gases from the melting and refining furnaces, before entering the CaL stage or the methanation stage in cases 1 and 2, respectively. Only the right amount of gas to produce the SNG required for the system is accepted into the next stage. Were all the flue gas accepted, the equipment would be oversized. The resulting purged flue gas in case 1 is a mixture of different compounds, being CO_2 part of it. However, in case 2 the purged gas is water and CO_2, which offers the possibility of storing it for further uses, such as selling. As a summary, CO_2 emissions in case 1 are higher because they include not only the annealing furnace (which is not included in the power-to-gas integration), but also the purged flue gas that cannot be integrated. Meanwhile, CO_2 emissions in case 2 are lower as they only comprise the annealing furnace. The purged flue gas in case 2,which will be later stored or sold, is computed in KPI 8 (CO_2 stored). Case 1 presents the highest energy penalty (KPI 9), as more electricity is needed to abate less CO_2 emissions. When

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self-produced energy is considered, the energy penalties are reduced by 25% with PV production and 47% with WF production.

Table 2: Comparison of KPIs for the low-carbon concepts (P: Purchased; PV: Photovoltaic self-consumption; WF: Wind farm self-consumption)

KPI	Related to	Description	Units	Case 1	Case 2
1	CaL	CO_2 energy requirements	kWh_t/kg_{CO2}	0.726	-
2	CaL	CaL energy requirements	kWh_t/t_{glass}	214.2	-
3	PtG	SNG production	kg_{SNG}/t_{glass}	115.3	91.74
4	Rankine	Electricity generation	kWh_e/t_{glass}	346.9	-
5	PEM	Electrolyzer consumption	kWh_e/t_{glass}	2287	1899
6	Operation	Net electricity consumption	kWh_e/t_{glass}	2194	2146
7	Operation	CO_2 emission	kg_{CO2}/t_{glass}	45.46	12.01
8	Operation	CO_2 stored	kg_{CO2}/t_{glass}	0	50.01
9	Operation	Energy penalty	MJ/kg_{CO2}	*P:* 27.9 *PV:* 21.0 *WF:* 14.8	*P:* 24.1 *PV:* 18.1 *WF:* 12.7
10	Economics	20-year balance	M€	*P:* -92.9 *PV:* -75.2 *WF:* -56.8	*P:* -81.7 *PV:* -63.2 *WF:* -44.2
11	Economics	CAPEX	M€/y	*P:* 35.4 *PV:* 57.6 *WF:* 82.8	*P:* 15.7 *PV:* 37.3 *WF:* 61.9
12	Economics	Incomes	M€/y	9.60	8.06
13	Economics	OPEX	M€/y	*P:* 13.8 *PV:* 10.9 *WF:* 7.69	*P:* 12.9 *PV:* 10.0 *WF:* 6.76
14	Economics	Carbon abatement cost	$€/t_{CO2}$	*P:* 282 *PV:* 197 *WF:* 253	*P:* 234 *PV:* 157 *WF:* 181
15	Economics	Specific Implementation Cost	$€/t_{glass}$	*P:* 83.3 *PV:* 58.0 *WF:* 74.8	*P:* 57.4 *PV:* 38.4 *WF:* 44.3

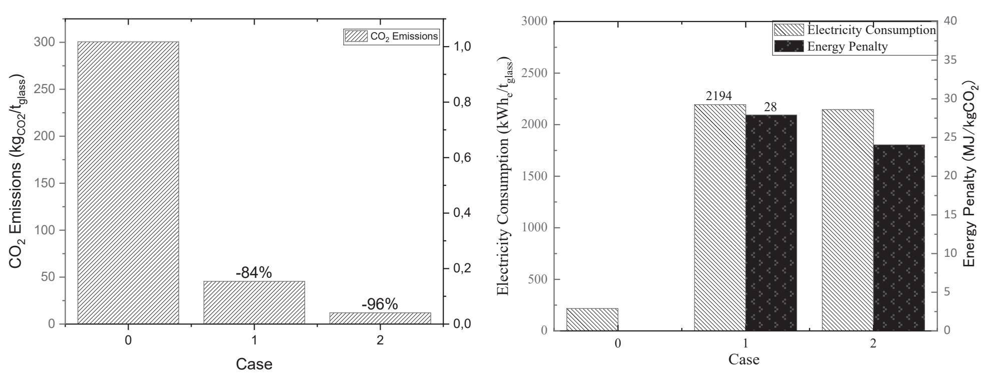

Figure 3: Left: CO_2 emissions (kg_{CO2}/t_{glass}) and their relative reductions respect to Case 0. Right: Net electricity consumption (kWh_e/t_{glass}) and energy penalty (MJ_e/kg_{CO2}).

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3.2 Economic analysis

KPIs 10 to 15 are presented in Table 2. Two separate analyses can be drawn out, depending whether one examines the differences between economic scenarios or the difference between cases. KPI 10 (20-year balance) allows differentiating between economic scenarios. WF self-generation offers the best economic results (-39% compared with full purchase), followed by PV self-generation. Even though the wind farm presents the highest required capital expenditure (KPI 11), it also presents the highest capacity ratio, allowing for a comparatively lower operational expenditure (KPI 13) than a photovoltaic plant (-32%). As incomes (KPI 12) are independent of the electricity production regime, WF results in better benefits, allowing them to reach break-even point. The pattern differs when KPIs 14 (Carbon Abatement Cost) and 15 (Specific Implementation Cost) are considered, as photovoltaic presents a more satisfactory result than WF generation, due to the lower CAPEX incurred by the PV plant.

Economic results are clearly better for case 2, as it presents a lower CAPEX (KPI 11) and OPEX (KPI 13), as well as a lower carbon abatement (KPI 14) and specific implementation cost (KPI 15). Case 1 only scores better in the yearly incomes (KPI 12) Still, it is not enough to compensate the higher costs, resulting in a worse 20-year balance (KPI 10) than case 2.

KPI 12 (income) is 19% higher in case 1 thanks to the sale of all the by-produced excess O_2, which makes up for the lesser amount of CO_2 emissions avoided in case 1. Although case 2 presents an additional revenue thanks to the sale of the excess CO_2, it is comparatively small compared to the sold O_2 in case 1. KPI 13 (OPEX) is higher in case 1 due to the electrolyzer electricity consumption, representing the majority of the cost. Case 2, with the smaller electrolyzer size, presents the best result, with a 17% reduction regarding case 1. KPIs 14 (Carbon abatement cost) and 15 (Specific implementation cost) are the highest in case 1, as it presents worse benefits and higher CO_2 emissions.

An analysis regarding the plant size is conducted regarding the 20-year balance and the carbon abatement cost (Figure 4), as the high imbalances between CAPEX and benefits in the different cases may have a great effect when size is considered. An economic scenario of wind farm self-generation, offering the best economic benefits, is considered. As expected, the oxy-combustion configuration presents better results than case 1, independently of the KPI analysed and of the plant size.

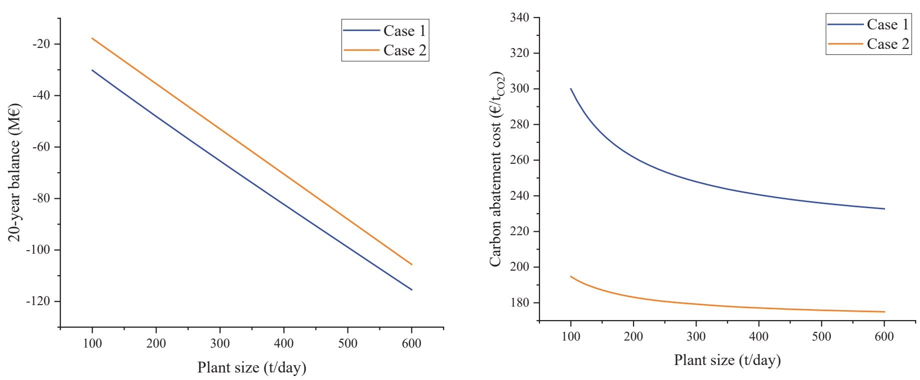

Figure 4: Sensitivity analysis varying plant size of KPI10 (left) and KPI14 (right)

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4 CONCLUSION

The current work compares two different power to gas integrations in the glassmaking industry, simulated in Aspen Plus. Fossil natural gas is substituted by synthetic natural gas, produced within the bounds of the industry in a methanation reactor, forming a closed loop. This is achieved by combining green H_2 produced in a PEM electrolyzer with a CO_2 stream. Case 1 features a calcium looping (CaL) capture plant as the way of obtaining the CO_2, whereas case 2 is based on oxycombustion operated with O_2-CO_2 atmosphere.

The CaL-based integration takes advantage of the existing synergies in the glassmaking plant. CaL purge, composed of CaO, can be used as substitution of the $CaCO_3$ in the raw material, and waste heats from the CaL and methanation plants are recovered in a Rankine power plant to reduce the electricity demand. Meanwhile, the need of a carbon capture system is avoided under oxy-combustion conditions, as a pure CO_2 + water stream is directly obtained. The required O_2 is obtained as a by-product of the electrolyzer, needed to produce H_2 for the methanation reactor. Case 2 offers a quick solution for existing glassmaking plants that stride to reduce their emissions without changing the furnace.

The scenarios are compared from a techno-economic point of view, in which three economic scenarios have been taken into account: full electricity purchase, self-production via a photovoltaic plant, and self-production via a wind farm. Case 2 presents a 96% reduction in CO_2 emissions, compared to 84% in case 1. These results come at the expense of high electricity consumption, mainly related to the electrolyzer needs.

Economic results vary in function of the electricity origin. No scenario is profitable with the current prices, mainly due to the electrolyzer consumption. Therefore, they benefit from self-generation. Wind energy presents the best results, as the capacity factor is higher than in the case of photovoltaic production, enough to counter the higher investment costs of the wind farm. No clear conclusion can be made regarding which configuration is better. Although it is clear that the oxy-combustion integrations are more favourable, their performance varies between KPIs. Case 2 presents the lowest carbon abatement cost (181€/t_{CO2}) and specific implementation cost, (38.4 €/t_{CO2}).

As a conclusion, power-to-gas is a promising concept for CO_2 abatement in the glassmaking industry. The usage of oxy-combustion and self-produced renewable electricity can be combined to reduce the external electricity consumption of the plant, making it potentially profitable in the medium term.

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