Integration of Power-To-Methane into Glass Melting Processes

Sebastian Gärtner[1,2](✉), Daniel Rank[1], Michael Heberl[1], Matthias Gaderer[2], and Michael Sterner[1]

[1] Research Center on Energy Transmission and Storage (FENES), Technical University of Applied Sciences (OTH) Regensburg, Seybothstrasse 2, 93053 Regensburg, Germany
s.gaertner@tum.de

[2] Chair of Regenerative Energy Systems (RES), Campus Straubing for Biotechnology and Sustainability, Technical University Munich, Schulgasse 16, 94315 Straubing, Germany

Abstract. The glass industry is facing increased challenges regarding climate protection targets and rising energy costs. The integration of renewable energy including conversion and storage is a key for both challenges in this energy-intensive industrial sector, which has been mainly relying on fossil gas so far. The options considered to this point for reducing CO_2 emissions and switching to a renewable energy supply involve far-reaching changes of the established melting processes. This entails significant risks in terms of influences on glass quality and stable production volumes. The presented approach for the integration of a Power-to-Methane (PtM) system into the glass industry is a completely new concept and has not been considered in detail before. It allows the use of established oxyfuel melting processes, the integration of fluctuating renewable energy sources and a simultaneous reduction of CO_2 emissions by more than 78%. At the same time, natural gas purchases become obsolete. A techno-economic evaluation of the complete PtM process shows, that 1,76 €/m^3 or 1,26 €/kg synthetic natural gas are possible with renewable energy supply. Using electricity from the energy grid would require electricity prices $<$ 0,126 €/kWh to allow cost competitive PtM processes in the glass industry. Such electricity prices could be achieved by electricity market-based optimization and operation of the PtM system. This operation strategy would require AI-based algorithms predicting availabilities and prices on future-based markets.

Keywords: Power-to-Gas · Methanation · Glass Melting · Glass Industry · Decarbonisation

1 Introduction

More than 80% of the German glass industry's energy demand is currently covered by fossil fuels, such as natural gas (NG) and crude oil [1]. Since the resulting high greenhouse gas emissions are incompatible with international climate protection targets, the glass industry is facing increasing pressure to reduce its fossil fuel consumption. In

P. Schossig et al. (Eds.): IRES 2022, AHE 16, pp. 147–161, 2023.
https://doi.org/10.2991/978-94-6463-156-2_12

addition, the recent Russia-Ukraine crisis led to considerable increase in energy prices, especially of NG, the most important energy source of the glass industry (73% of energy demand [1]). Thus, the glass industry is also facing considerable economic pressure to achieve a rapid shift out of fossil fuels.

Solutions that have been discussed with regard to climate protection targets, such as all-electric melting or pure hydrogen combustion, still require further research and development to be used in a robust process on an industrial scale [2–5]. Thus, innovative solutions for a quick implementation are needed to achieve this rapid transition. At the same time, stranded assets of established fossil fuel melting tanks must be avoided. Depending on molten glass type, these tanks can be designed for a lifetime of more than ten years [6].

A promising option to meet these demands, is the integration of a Power-to-Methane (PtM) process into oxyfuel glass melting systems [2]. This process is described in more detail below.

1.1 Power-To-Methane in Glass Melting Processes

Figure 1 shows a simplified flowsheet of the integration of a PtM process into oxyfuel glass melting systems.

In a first step, water is separated into hydrogen (H_2) and oxygen (O_2) by water electrolysis. The required electricity for the electrolyser can either be generated by intermitting renewable energies such as wind and solar or consumed from the energy grid. In case of renewable energy supply, a H_2 and O_2 storage system is necessary to balance the fluctuations of such renewable energy sources.

The produced H_2 is subsequently used in a thermochemical methanation process. Thereby, H_2 and carbon dioxide (CO_2) form methane (CH_4) and water (H_2O), within the so-called Sabatier process [7]. This methanation is performed using a catalyst at process temperatures of 200–600 °C and a pressure of 20–80 bar. The resulting gas mixture, consisting mainly of CH_4, is commonly referred to as synthetic natural gas (SNG).

Since NG also consists mainly of CH_4, this SNG can be substituted for NG, and be used in a former fossil fuel fired glass melting tank. The PtM process is particularly attractive in combination with oxyfuel fired melting tanks. In this case, NG or SNG is not combusted in ambient air, but in an atmosphere of almost pure O_2. This results in higher flame temperatures and better mass transport in the melting tanks, due to the absence of nitrogen in the furnace atmosphere. The flue gases of this combustion type ideally consists solely of CO_2 and H_2O vapor. In conventional oxyfuel glass melting, the required oxygen for combustion must be produced via energy intensive air separation units (ASU). However, by integrating the designed PtM process into glass melting, O_2 can instead be obtained as a side product of electrolysis [8].

After the glass furnace, the flue gases are commonly cleaned in filter systems to comply with country-specific emissions limits, which usually relate to NO_x, SO_x and dust compositions. The remaining cleaned flue gases are still rich on CO_2 and can be brought into a CO_2 separation unit. In particular CO_2 capture with absorption based post-combustion processes is a suitable option for the PtM process. The application of this CO_2 capture technology is described and investigated in detail in [8]. The resulting CO_2 stream can subsequently be recycled to the methanation process.

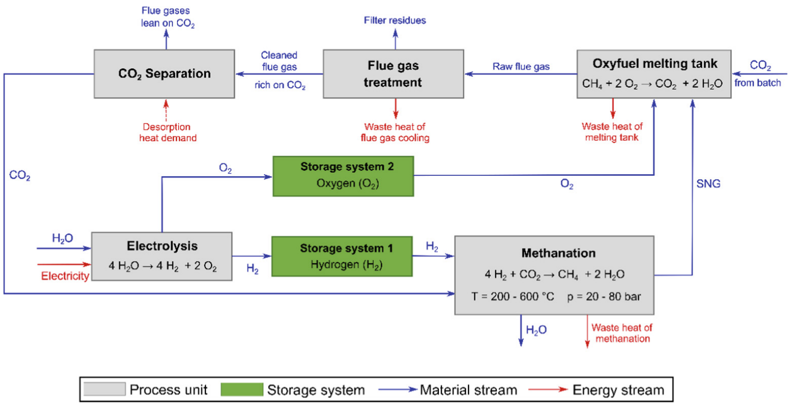

Fig. 1. Flowsheet of the integration of a Power-to-Methane process into oxyfuel glass melting. [8]

The PtM process thus creates an almost closed CO_2 cycle, which allows a considerable reduction in environmentally harmful emissions. Furthermore, energy from fluctuating renewable energy sources can be integrated into the glass industry, without having to modify proven melting processes. In addition, a rapid shift away from NG can be achieved, as all process steps such as electrolysis, methanation and CO_2 capture are commercially available and are at high technology readiness levels.

1.2 Scope of This Work

Previous work by the authors focused on the simulation and techno-economic analysis or a Power-to-Hydrogen process for oxyfuel glass melting [2]. In a further study, the PtM process was presented and the CO_2 capture form the flue gases of glass melting processes was investigated in detail [8]. Based on the authors' previous work, this paper aims on the further investigation of the changes in the specific energy demand and the specific CO_2 emissions of the PtM process. In addition, a techno-economic analysis for renewable energy supply and grid purchase of electricity will be carried out.

2 Methods

The basic methodology is adapted from previous work of the authors which involved the simulation and techno-economic analysis of the integration of a Power-to-Hydrogen (PtH_2) concept into the glass industry [2]. Changes and extensions to the methods described there are explained in more detail below.

2.1 Modelling and Simulation

For physical modelling, the acausal programming language Modelica is used [9]. Simulations were performed in the editor Dymola 2023.

Table 1. Existing [11] and assumed new renewable energy sources at case study location.

Wind Power			
Existing		New	
Plants	Hub height	Plants	Hub height
2 x AN Bonus 600 kW	58 m	13 x Siemens SWT-4.0–130 4000 kW	90 m
1 x AN Bonus 1000 kW	70 m		
Photovoltaics			
Type	**Power**	**Type**	**Power**
Open field	3500 kW	Open field	14.000 kW

2.1.1 Renewable Energy

The models of the TransiEnt library are used for the wind and photovoltaic plants shown in Table 1 [10]. In previous work it was found, that the energy demand of the PtH_2 concept for oxyfuel glass melting cannot be met by renewable energy sources at the specific case study location in Steinberg am Wald, Bavaria, Germany [2]. The location can be considered one of the main centres of the German container glass industry. The nearby renewable energy park consists of the wind power (WP) and photovoltaic power plants (PV) shown in Table 1.

The repowering scenario for the renewable energy sources assumed a significant increase of the existing plants. The new power capacities are also shown in Table 1.

2.1.2 Power-To-Methane Process

The mass balance of the Power-to-Methane system is based on the reaction equations of electrolysis and methanation:

$$2H_2O \rightarrow 2H_2 + O_2 \tag{1}$$

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \tag{2}$$

The influence of the electrolysis efficiency on the H_2 production was modelled as described in [2]. The thermochemical methanation is adapted from [12].

2.1.3 Oxyfuel Melting

For this work, a glass melting tank with the properties shown in Table 2 is assumed. All physical modelling of combustion, heat transfer and batch-to-melt conversion is adapted from [2].

2.1.4 *CO_2 Capture from Flue Gases*

In [8], a concept for CO_2 capture from the specific flue gases of glass melting plants has been developed, modelled, and evaluated in terms of separation costs. A post-combustion

Table 2. Parameters of the investigated melting tank [2]

Parameter	Value
Pull rate	100 t/d
Burner power	4.965 kW
Melting technology	Oxyfuel
Efficiency	42%
Electrical Boosting	10% of burner power
Glass type	Soda-lime
Standard enthalpy	550 kWh/t
Cullet fraction	50%
Glass exit temperature	1350 °C

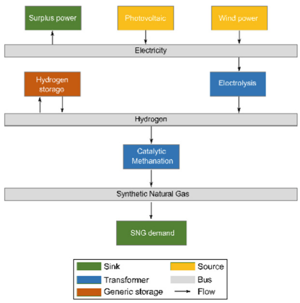

Fig. 2. Block diagram of the OEMOF energy system.

absorption system using monoethanolamine (MEA) as solvent was identified as the best option for CO_2 capture. Due to the high waste heat potentials in the glass melting process and the PtM concept, low capture costs of approx. 42 €/t CO_2 could be demonstrated and will be used in the context of the economic analysis in the present work [8].

2.2 Economic Optimization

The OEMOF optimization model of [2] is extended to include methanation as a H_2 consumer. The block diagram of the extended OEMOF energy system is shown in Fig. 2.

2.3 Cost Parameter Assumptions

Capital expenditures (CAPEX) 900 €/kW are assumed for electrolysis, according to [13]. In this work we assume that H_2 is stored in overground pressure storage tanks. Investment costs of 11,00 €/kWh are reported in [14] for this type of H_2 storage. According to [13], CAPEX of 580 €/kW SNG can be assumed for a 5 MW catalytic methanation reactor. As shown in Table 2, this methanation power is sufficient to meet the thermal power demand of the melting tank. The operational expenditures (OPEX) of this process equipment are assumed to be 3% of CAPEX per year.

Electricity and water must be purchased to supply energy and raw materials for the PtM process. A price range of 0,03–0,11 €/kWh for electricity from open field PV, and 0,04–0,08 €/kWh for WP is reported in [15]. In this work, 0,06 €/kWh both for electricity from PV and WP were assumed. In addition, 0,50 €/m^3 of tab water are assumed, as an electrolysis feedstock. The cost for CO_2 capture from flue gases of the glass industry are calculated in [8]. Due to small plant size and multiple waste heat usage options in the PtM process, 42 €/t CO_2 can be achieved.

2.3.1 Avoided Cost Assumptions

The investment and operating costs of the PtM process, can be compared to immediately avoided natural gas, avoided O_2 and avoided costs for CO_2 certificates in the future.

Due to the current energy crisis in Central Europe, natural gas costs are currently highly dynamic and unpredictable. While 0,36 €/m^3 or 0,03 €/kWh were realistic purchase prices just a few years ago (2018), they are currently more than 2,20 €/m^3 or 0,20 €/kWh on the relevant trading exchanges (2022). In this work, the two price scenarios for natural gas (NG) 2018 and natural gas 2022 are compared.

O_2 is usually delivered to glass original equipment manufacturers (OEM) and stored in pressure tanks or produced on site using air separation units. Also in this case, dependencies on energy costs have changed prices significantly. While 0,10 €/Nm^3 have been assumed in [2], we have assumed 0.125 €/Nm^3 in this work to reflect these cost developments.

At present, glass OEM, are not yet subject to emission trading, because they are considered as an industry exposed to the risk of carbon leakage. Therefore, no cost occurred for glass OEM for CO_2 emissions. However, the German glass industry sector hast to report its CO_2 emissions in [16]. Nevertheless, costs for emissions may also arise for these companies in the near future. Since CO_2 emissions must be reported under the European Union Emission Trading System (EU ETS) already, this work assumes that these costs and trading systems will serve as a basis. CO_2-emission certificates are traded at the European Energy Exchange (EEX). Prices at EEX fluctuated between 75,80 €/EUA and 89,77 €/EUA from June to August 2022 (see Fig. 3) [17]. The average price was 82,39 €/EUA. Therefore, 82,00 €/t CO_2-eq. Are assumed for avoided CO_2 emission costs in this work.

3 Results and Discussion

In this section, the results of our investigations are show. First, we present the influences on specific energy demand and CO_2 emissions. Afterwards, the results of a cost calculation study will be presented.

3.1 *Specific Energy Demand and CO_2 Emissions*

The specific energy demand of the conventional oxyfuel melting process, including the energy demand of O_2 generation and electrical boosting is 1425 kWh/t glass. This number is in good match with [2]. By integrating the PtM process, the specific energy demand

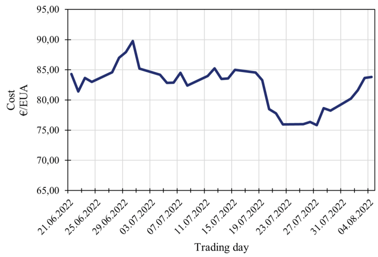

Fig. 3. Costs of European Union Allowances (EUA) for one ton of CO_2-eq. Emission on the European Union Exchange (EEX) from June 2022 until August 2022 [17].

increases to 2034 kWh/t glass. This increase of about 43% is caused by the energy losses in the electrolysis (+426 kWh/t glass) and methanation process (+ 298 kWh/t glass). The energy demand of the air separation unit is eliminated by integrating the PtM process, since oxygen can be provided by electrolysis. Figure shows an overview and a comparison of each contributing energy demand factor (Fig. 4).

Despite the increase of energy demand, the PtM process can significantly reduce CO_2 emissions, if renewable energy sources are used (Figure). While the specific emissions are at about 418 kg CO_2-eq./t glass for the conventional oxyfuel melting process, they are reduced to 91 kg CO_2-eq./t glass (i.e. −78%) in the renewable energy scenario. However, electrical boosting is still operated with gird electricity, as intermitting energy supply would cause reduced glass quality in this case.

The significant reduction in specific emissions is mainly caused by the low CO_2 emission factor of renewable electricity (0.019 kg CO_2-eq./kWh [2]), and the captured CO_2 evaporating from glass batch. While the CO_2 emissions form glass batch were at about 80 kg CO_2-eq./t glass in the conventional process, they are reduced by 95% via the capture rate of the CO_2 separation process from flue gases within the PtM process.

If electricity from the energy grid is used, the specific CO_2 emission factor of the energy mix for a specific country must be considered. In Germany, this mix caused 0,427 kg CO_2-eq /kWh in 2019 [18]. If this energy mix is used to cover the energy demand of the electrolysis, the specific CO_2 emissions of the entire PtM glass melting process add up to 872 kg CO_2-eq./t glass. These are more than two times (i.e. +208%)

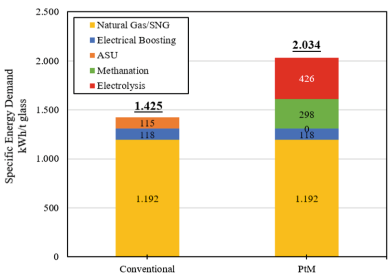

Fig. 4. Specific energy demand of the conventional oxyfuel melting process vs. the integration of a PtM process.

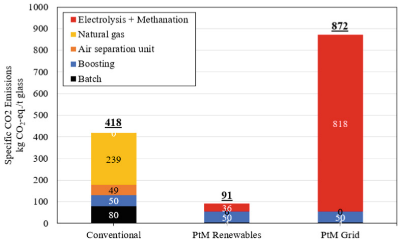

Fig. 5. Changes of specific CO_2 emissions of the conventional melting process vs. Power-to-Methane (PtM) with renewable energy sources (0,019 kg CO_2-eq./kWh, [2]) and the German grid energy mix (0,427 kg CO_2-eq./kWh).

the emissions of the conventional scenario. Figure shows the specific CO_2 emissions of each discussed scenario.

At an emission factor of less than 0.190 kg CO_2/kWh, the specific emissions of the PtM process for the glass industry would be lower than those of the conventional scenario.

3.2 Cost Calculation

In this work, two different cost scenarios are analysed. In the first scenario, only renewable energy sources are used for the power supply of the PtM process (Sect. 0). These investigations are based on a case study for a specific glass industry site in the north of Bavaria, Germany, similar to previous work of the authors [2]. At this location, container glass manufacturers are represented who would have sufficient melting capacities and produce suitable glass types for a quick implementation of the PtM process.

In the second scenario, electricity from the German grid is used for the PtM system. While the first scenario allows a maximum reduction of CO_2 emissions, the second scenario is intended to show the electricity costs at which a cost benefit over conventional natural gas can be achieved by the PtM process (Sect. 3.2.5).

3.2.1 Avoided Costs

In addition to spending, savings can also be achieved by the PtM process. As described in Sect. 2.3.1, costs for the purchase of natural gas, oxygen supply and CO_2 emission certificates can be avoided. To quantify these savings more precisely, the required NG and O_2 demand was calculated for the melting tank described in Table 2. The consumption and costs are shown in Table 3.

As can be seen in Table 3, natural gas costs have the largest impact on potential savings. While the costs for glass OEM were around 1,5 Mio. € in 2018, they are 9,2 Mio. € in the natural gas 2022 scenario. This is a six-fold increase in costs for natural gas supply. At around 1,1 Mio. €, avoided O_2 costs also represent a significant saving potential. In comparison, costs for CO_2 emission certificates are relatively low at around 680.000 €, despite the high costs of 82,00 €/t CO_2-eq.

Table 3. Assumed cost parameters for avoided purchase of operating resources. NG = Natural Gas.

	Volume	Specific Costs	Costs €
NG 2018	4.203.455 Nm^3	0,36 €/m^3	1.513.244
NG 2022		2,20 €/m^3	9.247.601
Oxygen	9.300.677 Nm^3	0,125 €/Nm^3	1.162.585
CO_2 cert.	8.407 t CO_2-eq.	82,00 €/t CO_2-eq.	689.367

Table 4. Performance data and parameters for investment costs in plant components.

	Renewable energy scenario		German grid scenario	
Methanation	5 MW	2,90 Mio. €	5 MW	2,90 Mio. €
H_2 Storage	809 MWh	8,90 Mio. €	-	-
Electrolysis	13,6 MW	12,25 Mio. €	8.9 MW	8,48 Mio. €
Total:	**24,00 Mio. €**		**11,38 Mio. €**	

3.2.2 Capital and Operational Expenditures

For every economic analysis, the capital expenditures (CAPEX) of the individual process steps must be determined. In addition, energy requirements and raw material costs must be quantified.

As described in Sect. 2.3, a 5 MW catalytic methanation reactor is 2,9 Mio. €. Since thermochemical methanation offers no flexibility options, the investment costs are the same for both economic scenarios. The optimization model, described in Sect. 2.2, found an electrolysis power of 13,6 MW. For the German grid scenario an electrolysis power of 8,9 MW is sufficient to ensure a sufficient H_2 supply of methanation (see Table 4).

For the renewable energy scenario, the optimization model estimated 809 MWh of H_2 storage capacity. In the German grid scenario, no H_2 storage is required since sufficient supply of electricity can be assumed to enable steady state operation of the PtM process. Table 4 shows the investment costs for the process equipment of each techno-economic scenario.

3.2.3 Renewable Energy Sources

Both the PV and wind power plants generate approx. 133 GWh of electricity during a test reference year [19]. The generated power profile of these renewable energy sources is shown in Fig. 6.

The PtM process consumes 78 GWh during the TRY, i.e. 59% of the produced energy. The excess power can be supplied to the grid. A reduction in renewable energy power would require larger H_2 storage capacities, since this would significantly reduce the full load hours of the electrolysis.

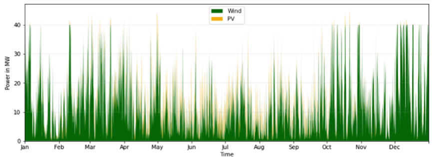

Fig. 6. Modeled power profiles of renewable energy sources at the case study location**.** Steinberg am Wald, latitude**.** 50.404387° longitude**.** 11.332333° (WGS84 coordinates).

3.2.4 Renewable Energy Supply Scenario

In the renewable energy scenario, the designed electrolysis unit produces approx. 1.500 t, or 17,6 Mio. Nm3 of H_2 during a TRY. Based on EAC-rates and OPEX for the electrolysis, H_2 storage system and the costs for energy and operating resources, the resulting H_2 production costs are 4,44 €/kg. Table 5 shows the yearly CAPEX and OPEX costs for the renewable energy supply scenario.

The costs for energy and operating resources through a TRY are shown in Table 6.

Based on the annual costs in Table 5 and the operating material costs from Table 6, the SNG production costs are determined. These costs are 1,76 €/m^3 or 1,26 €/kg SNG.

Table 5. Investment (CAPEX) and operating (OPEX) cost of the PtM process with renewable energy supply. Yearly total cost is EAC-rate + OPEX.

	Power	CAPEX		OPEX
	Capacity	Total	EAC-Rate	
		€	**€/a**	**€/a**
Electrolysis	13,6 MW	12.251.000	367.527	368.000
H_2 Storage	809 MWh 20.536 kg	8.900.000	714.186	267.000
Methanation	5,0 MW	2.900.000	232.704	87.000
	Sum:	**24.051.000**	**1.929.935**	**721.538**
		Total cost:	**2.651.472**	

Table 6. Costs for energy and operating resources of the PtM process with renewable energy supply. The costs for CO_2 captured from flue gases are based on [8].

	Demand	**Specific cost**	**Total cost per year**
Electricity	78 GWh	0,06 €/kWh	4.695.840 €
Water	14.167 m^3	0,50 €/m^3	7.084 €
CO_2	8.662.195 kg	0,42 €/kg	363.812 €
		Sum:	**5.066.736 €**

Table 7. Comparison of expenditures and avoided expenditures for the PtM process with renewable energy sources. Natural gas costs in 2018 are compared with present costs in 2022.

Expenditures		
SNG	−7.718.208 €	
Avoided Expenditures		
	2018	**2022**
Natural gas	1.513.244 €	9.247.601 €
Oxygen	1.162.585 €	1.162.585 €
CO_2 certificates	689.367 €	689.367 €
Sum:	**3.365.195 €**	**11.099.552 €**
±:	**−4.353.013 €**	**3.381.344 €**

Comparing these expenditures of the PtM process with renewable energy sources to the avoided expenditures results in the cost structure shown in Table 7.

In 2018, the PtM process would not have been cost-effective in this operating strategy, even with the high costs of 82,00 €/t CO_2-eq. For this time. However, in the 2022 cost scenario, the high avoided natural gas costs already result in savings of around 3,4 Mio. € in the first year of operation, compared to conventional energy supply. These enormous natural gas costs account for most of the savings (83%), while avoided O_2 purchases (11%) and CO_2 certificates (6%) are comparatively low and contribute only 17%.

3.2.5 German Electricity Mix

Despite the high CO_2 emissions caused by grid-based operation of the PtM process, this mode of operation can be useful for a glass OEM due to the lack of renewable energy sources. Therefore, the cost structure for this scenario will be discussed in this section.

As shown in Table 4, the CAPEX is 11,4 Mio. €. This is less than half the cost of the renewable energy scenario. The avoided investment for H_2 storage and the reduced electrolysis power requirement results in this massive cost benefits. This also results in significantly reduced annual costs of approx. 1,20 Mio. €/a, as shown in Table 8. This is about 1,45 Mio €/a less than in the renewable energy scenario (see Table 5).

The energy demand of the electrolysis, as well as water and CO_2 demand are the same as in the scenario with renewable energy supply, as the same amount of SNG must be provided by the PtM process. The time-constant operation has no influence on the required quantities of resources, only on their storage and availability. Therefore, costs for water and CO_2 are the same as in the scenario of Table 6. Therefore, the avoided expenditures for O_2 and CO_2 certificates are also the same and add up to about 1,85 Mio. €.

The electricity costs are the remaining decisive factor for the profitability of the PtM process, when operated with grid electricity. As shown in Fig. 7, an electricity price of <0,126 €/kWh is essential to achieve lower SNG production costs than current purchase

Table 8. Investment (CAPEX) and operating (OPEX) cost of the PtM process with grid energy supply. Yearly total cost is EAC-rate + OPEX.

	Power	CAPEX		OPEX
	Capacity	**Total**	**EAC-Rate**	
		€	**€/a**	**€/a**
Electrolysis	8,9 MW	8.035.714	644.807	241.071
Methanation	5,0 MW	2.900.000	232.704	87.000
	Sum:	**24.051.000**	**877.510**	**328.071**
		Total cost:	**1.205.581 €/a**	

prices for natural gas. If these saving factors are not considered, electricity costs of < 0,103 €/kWh are required for a cost-efficient PtM process.

These low electricity costs could be considered realistic for glass OEM in recent years. However, rising electricity costs can be expected in the future due to possible restrictions in primary energy markets in Europe, or increased climate protection efforts.

One option to have access to such low electricity prices in the future could be the participation in volatile markets, such as the day-ahead. By integrating an H_2 storage system, as described in Sect. 3.2.3, energy could be purchased in times of very low or even negative electricity prices. However, this would require electricity market-based optimization and operation of the electrolysis and storage system. As a starting point, a short-term (daily) storage option of the PtM process could be considered. The operation mode might be controlled by AI-based algorithms predicting availabilities and prices on future-based markets. This would allow rapid implementation of the PtM system, while developing a sustainable, grid-supporting operating strategy at the same time, as more and more renewable energy gets integrated into the power system.

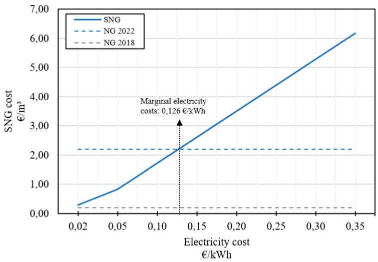

Fig. 7. Impact of electricity costs, when purchased from grid, on the cost of SNG from the PtM process. At electricity costs < 0.126 €/kWh, SNG from PtM is cheaper than current natural gas prices of 2.20 €/m^3 or 0.20 €/kWh. Avoided expenditures for O_2 and CO_2 are included.

4 Conclusion

This work investigates the integration of a PtM system into oxyfuel glass melting processes. A survey on changes of specific energy demand and CO_2 reduction potential is conducted. Moreover, an economic analysis is performed to compare the production costs of SNG to conventional energy purchases, based on two scenarios**.** a) renewable energy supply and b) energy purchase from the German power grid. The following conclusions can be drawn:

- After the integration of a PtM system, the specific energy demand increases by 43% compared to a conventional oxyfuel melting process.
- Covering the energy demand of the PtM system with renewable energies, the specific CO_2 emissions are reduced by 78%. However, using the current German electricity, CO_2 emissions increase by 208%. Thus, an emission factor of < 0.190 kg CO_2 /kWh for grid electricity would be necessary to reach below the emissions of the conventional scenario.
- Using renewable energy sources, the investigated SNG production costs of 1,76 €/m^3 are competitive against current natural gas prices on trading exchanges. Avoided natural gas expenditures are currently the main factor for a positive viability, while avoided oxygen and CO_2 certificate costs can be considered negligible.
- Using electricity from the grid, costs of < 0,126 €/kWh are required to allow a profitable PtM process, compared to conventional natural gas and oxygen purchase.

This work highly motivates further research and development of PtM processes for the glass industry. Low electricity costs from grids could be achieved by focusing on AI-based purchasing and operating strategies in future-based electricity markets. Founded on this and previous work by the authors, a reliable starting point has been established to motivate rapid implementations of PtM pilot plants in each individual case of glass OEM.

References

1. F. Ausfelder, A. Seitz and S. von Roon, Flexibilitätsoptionen in der Grundstoffindustrie Methodik, Potenziale, Hemmnisse : Bericht des AP V.6 "Flexibilitätsoptionen und Perspektiven in der Grundstoffindustrie" im Kopernikus-Projekt "SynErgie", Jülich, Germany: Dechema, 2018.
2. S. Gärtner, D. Rank, M. Heberl, M. Gaderer, B. Dawoud, A. Haumer and M. Sterner, "Simulation and Techno-Economic Analysis of a Power-to-Hydrogen Process for Oxyfuel Glass Melting," *Energies,* p. 24, 21 December 2021.
3. C. Wulf and P. Zapp, "Analyzing the future potential of defossilizing industrial specialty glass production with hydrogen by LCA," in *Procedia CIRP - The 29th CIRP Conference on Life Cycle Engineering*, Leuven, Belgium, 2022.
4. M. Zier, P. Stenzel, L. Kotzur and D. Stolten, "A review of decarbonization options for the glass industry," *Energy Conversion and Management X,* vol. 10, no. May, p. 100083, 2021.
5. D. D. Furszyfer Del Rio, B. K. Sovacool, A. M. Foley, S. Griffiths, M. Bazilian, J. Kim and D. Rooney, "Decarbonizing the glass industry: A critical and systematic review of developments, sociotechnical systems and policy options," *Renewable and Sustainable Energy Reviews,* vol. 115, no. March, p. 111885, 2022.

6. J. J. Schep, " Experiences with an oxygen-fired container glass furnace with silica crown: 14 years—A world record?," in *Proceedings of the 69th Conference on Glass Problems*, Columbus, OH, USA, 2009.
7. M. Sterner, Bioenergy and renewable power methane in integrated 100% renewable energy systems, Kassel: Kassel University Press, 2009.
8. S. Gärtner, T. Marx-Schubach, M. Gaderer, S. Gerhard and M. Sterner, "Introduction of an Innovative Energy Concept for low Emission Glass Melting with Special Focus on CO_2 Capture from Flue Gases," *Under Review for Applied Energy,* 01 08 2022
9. Modelica Association, "Modelica® – A Unified Object-Oriented Language for Systems Modeling. Language Specification," 18 February 2021. [Online]. Available: https://modelica.org/documents/MLS.pdf. [Accessed 21 August 2022].
10. A. Senkel, C. Bode, J.-P. Heckel, G. Schmitz, C. Becker and A. Kather, "Status of the TransiEnt Library: Transient Simulation of Complex Integrated Energy Systems," in *Proceedings of 14th Modelica Conference 2021*, Linköping, Sweden, 2021.
11. Bayerisches Staatsministerium für Wirtschaft, Landesentwicklung und Energie, "Energie-Atlas Bayern," Bayerische Staatsregierung, 15 07 2022. [Online]. Available: https://www.energieatlas.bayern.de/energieatlas.html. [Accessed 15 07 2022].
12. A. Bader, S. Bauersfeld, C. Brunhuber, R. Pardemann and B. Meyer, "Modelling of a Chemical Reactor for Simulation of a Methanisation Plant," in *Proceedings 8th Modelica Conference*, Dresden, Germany, 2011.
13. A. Zauner, H. Böhm, D. Rosenfeld and R. Tichler, "Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimization - Analysis on future technology options and on techno-economic optimization," Store & Go, Falkenhagen, Germany, 2019.
14. B. Zakeri and S. Syri, "Electrical energy storage systems: A comparative life cycle cost analysis," *Renewable and Sustainable Energy Reviews,* pp. 569–596, 02 2015.
15. C. Kost, S. Shammugam, V. Fluri, D. Peper, A. D. Memar and T. Schlegl, "Stromgestehungskosten Erneuerbare Energien," Fraunhofer-Institut für Solare Energiesysteme (ISE), Freiburg, Germany, 2021.
16. Deutsche Emissionshandelsstelle (DEHSt) im Umweltbundesamt, Treibhausgasemissionen 2021 - Emissionshandelspflichtige stationäre Anlagen und Luftverkehr in Deutschland (VET-Bericht 2021), Berlin: Umweltbundesamt (UBA), 2022
17. European Energy Exchange AG, "Spotmarkt Umweltprodukte," Deutsche Börse Group, 05 08 2022. [Online]. Available: https://www.eex.com/de/marktdaten/umweltprodukte/spotmarkt. [Accessed 05 08 2022].
18. P. Icha and G. Kugs, "Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990–2019," Umweltbundesamt (UBA)- Climate Change, Berlin, Germany, 2020.
19. Deutscher Wetterdienst (DWD), "Projektbericht: Ortsgenaue Testreferenzjahre von Deutschland für Mittlere und Extreme Witterungsverhältnisse," 2017. [Online]. Available: https://www.dwd.de/DE/leistungen/testreferenzjahre/testreferenzjahre.html. [Accessed 09 September 2021].