Environmental Impacts of Using Hydrogen for Defossilizing Industrial Specialty Glass Production

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Abstract. The glass industry is part of Germany's energy-intensive industry. Today, mostly fossil energy carriers are used to produce the high temperatures needed, e.g., to melt the raw materials. One option to push defossilisation is the use of green hydrogen in the furnace. The strictest requirements regarding a steady heat supply has the specialty glass production. The hydrogen can be produced on-site in an electrolyzer, using not only the hydrogen for combustion but also the co-produced oxygen in the oxyfuel process. Alternatively, hydrogen can be produced off-site in a large scale electrolyzer to facilitate economy of scale. For transport and distribution of this hydrogen different options are available. Besides conventional high-pressure trailers a rather new option are liquid organic hydrogen carriers (LOHC), which allow hydrogen to be transported and stored at a higher volumetric density and to be treated in the same way as conventional fossil fuels. Temperatures necessary to separate the hydrogen from the LOHC after transport can be provided using waste heat from the glass melt. Another promising future option is the repurposed use of today's natural gas pipelines.

Environmental impacts of this example of the so-called sector coupling – shifting from conventional fossil-based combustion to the use of electrochemically produced hydrogen in combination with a transformation of the German grid mix towards renewable electricity – is being investigated by the means of a Life Cycle Assessment (LCA). The main objective is to evaluate which hydrogen-based solution to produce specialty glass has the least impact on climate change in a time frame from 2020 till 2050. Furthermore, the trade-offs for other environmental impacts are analysed. The results indicate that all hydrogen-based options offer a huge potential to lower greenhouse gas emissions in 2050 compared to today's fossil-based production. When local conditions permit an on-site hydrogen production this is the best option for hydrogen use in the glass production.

Keywords: Life Cycle Assessment · Specialty glass production · Hydrogen supply

1 Introduction

Fighting climate change does not only mean switching from fossil fuels to renewable energy sources for electricity generation, but also structural changes in the mobility

P. Schossig et al. (Eds.): IRES 2022, AHE 16, pp. 538–550, 2023.
https://doi.org/10.2991/978-94-6463-156-2_35

and the industry sector. Over the last years huge progress has been made reducing the carbon footprint of the electricity mix in Germany (a reduction of CO2-eq from 2000 to 2021 by 35% [2]). However, in the same time span the emissions from the industry sector decreased only by 13% [3]. As part of the energy-intensive industry the glass production needs large amounts of fossil energy carriers, mainly natural gas, or mineral oil. During the production process temperatures between 1000 and 1600 °C are reached to melt the raw materials. In 2021 the German glass industry emitted slightly more than 4 Mio. t. CO2-eq [4], which did not change much over the last years. Due to this slow defossilisation of the glass industry the German Federal Ministry of Education and Research (BMBF) decided to fund the Kopernikus P2X[1] (Power-to-X) to develop electrolytic hydrogen-based processes for the industry.

According to Zier, Stenzel, KotzurStolten [5] several possibilities exist to reduce carbon emissions in the glass industry. Glass recycling is the option that is already practised for years. So far, only container glass and glass fibres are collected. Several measures for process intensification and waste heat recovery are under investigation. However, most effective seems to be fuel substitution. In particular, the authors identified electric melting of the glass and/or substituting natural gas in the heating system by hydrogen as a promising option. In the Kopernikus P2X project first small scale tests in a real plant with hydrogen heating were successful [6]. In a first published Life Cycle Assessment (LCA) study [7] we evaluated different options for hydrogen supply for the production of specialty glass compared to conventional natural gas heating in specialty glass production. We looked at a timespan from 2020 to 2050. However, acceleration to decarbonize the German energy system in 2021 [8] was not considered at that time. Furthermore, the transport of hydrogen developed over the last years and in this study, we substantially updated hydrogen transport to the state of the art. Thus, the goal of this paper is to analyse the hydrogen heating in specialty glass production compared to natural gas heating with state-of-the-art hydrogen supply technologies and up to date energy system modelling data for 2020, 2030 and 2050.

2 Life Cycle Assessment Context and Process Description

To perform a transparent LCA first the main aspects of this methodology are illustrated and the goal and scope for the case study hydrogen heating in specialty glass production are introduced. This is followed by a detailed technology description of the analysed case study.

2.1 Life Cycle Assessment for Specialty Glass Production

LCA is an established methodology to evaluate environmental impacts of products and services. ISO standards exist for over a decade to establish a common ground [9, 10]. The main objective of this methodology is to include not only the operation phase of a process, but also the construction of the necessary equipment and – if possible – its end of life. Furthermore, resource and energy demands are not only considered for the so-called foreground system, but also for the background system, e.g. steel demand for the

[1] https://www.kopernikus-projekte.de/en/projects/p2x.

Table 1. Applied LCA impact categories based on ReCiPe 2016 [14]

Environmental impact category	Unit
Climate change	kg CO_2-eq
Particulate matter	kg $PM_{2.5}$-eq
Ozone depletion	kg CFC-11-eq
Photochemical ozone formation (POF)	kg NOx-eq
Acidification	kg SO_2-eq
Water consumption	m^3
Fossil depletion	kg oil-eq
Land use	annual crop-eq*a
Metal depletion	kg Cu-eq

construction of wind power plant to produce electricity. With the help of environmental impact assessment methods, e.g. GWP100 from the Intergovernmental Panel on Climate Change [11], the products and services are being assessed during the Life Cycle Impact Assessment (LCIA).

For the study presented in this paper the software GaBi 10.5 [12] was used. For the background data datasets from the commercial ecoinvent database 3.6 (cut-off system model) [13] were taken. Data for the foreground processes were gathered within the project 'Kopernikus Power-to-X'. The LCIA is performed with the method package ReCiPe 2016 [14] at midpoint level (H). However, not all impact categories are analyzed only those listed in Table 1. The others were excluded, because it was not possible to reproduce similar results across different LCA tools (GaBi, Umberto, SimaPro).

The functional unit for this LCA study is the production of specialty glass of one hour, which amounts to 1875 kg of specialty glass. The geographical focus is on Germany. Thus, wherever possible datasets with German conditions were used. Regarding the time frame, the reference year is 2020. Based on that, future systems for the years 2030 and 2050 were developed. For these prospective options, technological development as well as technology changes were taken under consideration for the foreground system. For the background system, the German electricity mix was adjusted based on an energy system modelling conducted for the project [1].

2.2 Process Description

Today's glass troughs for specialty glass production in Germany are heated with natural gas in many cases. Therefore, this process is chosen as a fossil reference to benchmark the hydrogen heating system for specialty glass production. The natural gas is burned in an oxyfuel process together with oxygen, which is produced in an air separation unit (Fig. 1).

The operation parameters of the specialty glass production are summarized in Table 2. The actual feedstock for glass production is not considered, because it is the same for all analysed options. The same applies for the construction of the glass trough.

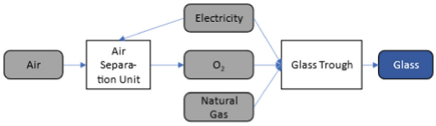

Fig. 1. Fossil reference process for specialty glass production

Table 2. Parameters of specialty glass production (Bauer et al. 2021)

	Natural gas	Hydro-gen	Unit
Hydrogen demand	–	450	kg/h
Natural gas demand	380	–	kg/h
Oxygen demand	4100	4100	kg/h
Electricity demand glass trough	600	600	kWh/h
Electricity demand air separation unit	0.4	0.4	kWh/Nm^3O_2
Operating hours	7875	7875	h/a

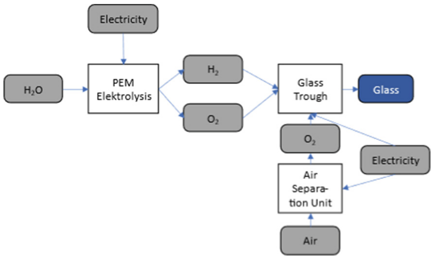

Fig. 2. Specialty glass production with hydrogen heating, on-site supply, PEM: Polymer electrolyte membrane

As a low-carbon alternative electrolytic hydrogen can be used for heating the glass trough. For the supply of hydrogen, here four different options are discussed. The first one is depicted in Fig. 2, where the hydrogen is produced on-site by a polymer electrolyte membrane (PEM) electrolyzer. For the subsequent oxyfuel combustion not only the hydrogen but also the oxygen from the electrolyser can be used. However, as the combustion of hydrogen is performed under excess air conditions some additional oxygen needs to be produced by the air separation unit.

For all hydrogen supply options the same PEM electrolyzer of 1 MW is assumed. For the period under consideration the development of the technology achieves improvements regarding the lifetime of the electrolyzer stack as well as the efficiency of the system (Table 3). The electrolyzer is assumed to be operated using electricity from the German grid mix, because specialty glass production is dependent on a constant supply of hydrogen. Electricity from renewable energy sources would only be able to provide this

Table 3. Operating parameters of the PEM electrolysis of 1 MW [15]

	2020	2030	2050	Unit
Lifetime PEM system	20	20	20	a
Lifetime stack	5	7	10	a
Electricity demand (including auxiliaries)	53.6	49.4	45.8	kWh/kg H_2
Water demand	9	9	9	kgH_2O/ kg H_2

with an elaborated electricity and hydrogen storage system. Thus, not green hydrogen is produced here.

Alternatively to the on-site production, hydrogen from a central hydrogen production facility can be transported to the glass production site. For the three considered hydrogen transportation options, high-pressure or Liquid Organic Hydrogen Carrier (LOHC) trailer and pipeline, a transport distance of 200 km was considered. From an economic perspective using electrolyzers larger than 1 MW for centralized hydrogen production is beneficial [16]. However, from an environmental perspective the differences between 1 MW and multi-MW electrolyzers is marginal [17]. Thus, for all hydrogen options a 1 MW electrolyzer is chosen here.

For the transport of hydrogen several technologies are available. Proven over years are the transport of gaseous hydrogen at a pressure level from 250 to 500 bar and the transport of liquid hydrogen at −253 °C (20 K). Both technologies have their advantages and disadvantages. In recent years a new technology has been developed to store hydrogen in organic compounds. The hydrogenated compound can be handled like conventional mineral oil products [18]. These compounds are called LOHC. As LOHCs several chemicals are under investigation, most of them toluene based. Over the time of the Kopernikus P2X project benzyl toluene (BT) has proven to be suitable best [19]. The first step is a hydrogenation reaction, where the hydrogen is bound to the BT. This is an exothermic reaction where heat at a temperature level of 250 °C is released. Correspondingly the dehydrogenation of the perhydro benzyl toluene (12BT) is endothermic and temperatures slightly below 300 °C are required. The chemical reaction is depicted in Eq. 1.

$$C_{14}H_{14} + 6H_2 \leftrightarrow C_{14}H_{26} \tag{1}$$

In specialty glass production a lot of excess heat is produced that can be used to dehydrogenate the hydrogen from the LOHC (Fig. 3).

Further technical parameters of hydrogenation and dehydrogenation are listed in Table 4.

The second roadbound hydrogen transport option discussed in this paper is liquid hydrogen. The whole process chain is comparable to the one with LOHC. The difference is that instead of the hydrogenation the hydrogen is liquefied. The electricity demand as well as the hydrogen loss for all years discussed are listed in Table 5.

The road bound transport (LOCH, liquid hydrogen) is performed in 2020 with conventional diesel trucks. For 2030 and 2050 it was assumed that fuel cell electric trucks

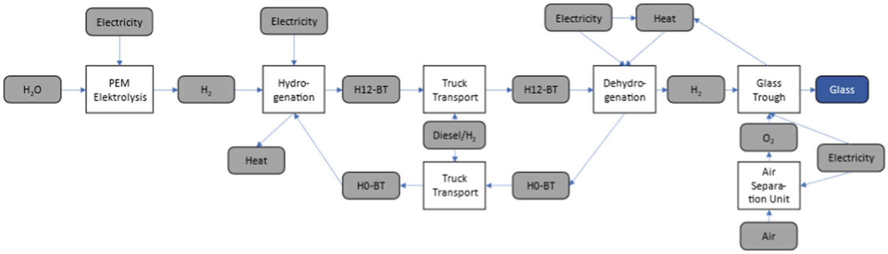

Fig. 3. Specialty glass production with hydrogen supplied by Liquid Organic Hydrogen Carrier (LOHC), BT: Benzyl toluene, PEM: Polymer electrolyte membrane

Table 4. Parameters of benzyl toluene hydrogenation and dehydrogenation [20]

	Hydrogenation	Dehydrogenation	Unit
Lifetime catalyst	4	4	a
Pressure level	30[a]	3	bar
BT - makeup	0.1	–	%/ cycle
Electricity demand	1	0.18	kWh/kg H2
Electric heat demand dehydrogenation	–	6.7	kWh/kg H2
Completeness of dehydration reaction[b]	–	85	%

[a]outlet pressure electrolyzer; [b]in 2020, in 2030 90% and in 2050 95%

Table 5. Liquefaction parameters [21, 22]

Electricity demand		
2020	10.3	kWhel/kg H2
2030	8.53	kWhel/kg H2
2050	6.76	kWhel/kg H2
Hydrogen loss	1.65	%

are widely available and will be used instead of diesel trucks. Fuel demand of the different truck types as well as the hydrogen transport capacity for the considered years are listed in Table 6.

As an alternative to road bound transport for 2030 and 2050 a hydrogen pipeline system in Germany is considered. This option is neglected for 2020 because today hydrogen is only locally transported in pipelines and not several hundred kilometres. A hybrid approach with a mix of newly built hydrogen pipelines and repurposed natural gas pipelines is assumed. According to Cerniauskas, Jose Chavez Junco, Grube, RobiniusStolten [24], for 2030 75% new constructed and 25% repurposed pipelines are considered and for 2050 54% new constructed and 46% repurposed. It is assumed that

Table 6. Transport parameters [20, 23]

	2020	2030	2050	Unit
Payload truck (net)				
LOHC	1530	1620	1710	kg H_2
Liquid H_2	3500	3900	4300	kg H_2
Diesel demand truck	39.9	–	–	l/100 km
Hydrogen demand truck	–	5.61	3.85	kg H_2/ 100 km

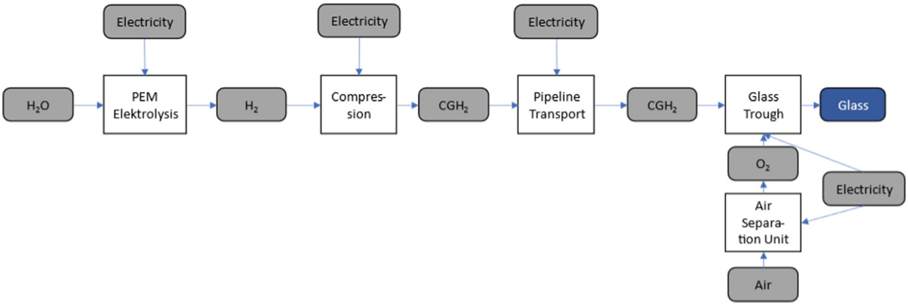

Fig. 4. Specialty glass production with hydrogen supplied by pipelines, CG: Compressed gaseous, PEM: Polymer electrolyte membrane

a pipeline has a lifetime of 80 years. For repurposed pipelines 40 years are allocated to natural gas transport and 40 years for hydrogen transport. The pipeline is operated at a pressure between 100 and 65 bar. Thus, the hydrogen needs to be compressed initially to 100 bar (Fig. 4). Modelling of the pipeline system is based on Wulf, Reuß [25].

The four hydrogen-based options rely heavily on electricity for hydrogen production and for hydrogen transport. Thus, including future developments of the German electricity mix is of utmost importance for this LCA study. Here the results of the energy system modelling of the project Kopernikus P2X were used for the years 2030 and 2050 [1]. These scenarios are based on goals of the German Climate Change Act 2021 [8]. This includes climate neutrality by 2045 and a reduction of greenhouse gas emissions by 65% in 2030 compared to 1990. The resulting electricity mixes are depicted in Fig. 5.

3 Results

The effect of the introduced hydrogen options at different years on the environmental impact Climate change is compared to natural gas based conventional production in Fig. 6. In the 2020 scenario, the results for all hydrogen-based heating options are dominated by hydrogen production emissions, which mainly stem from the current electricity mix. Therefore, the conventional heating of the glass trough with natural gas causes significantly less greenhouse gas (GHG) emissions. However, considerable differences are evident between the hydrogen options. On-site hydrogen production benefits not only

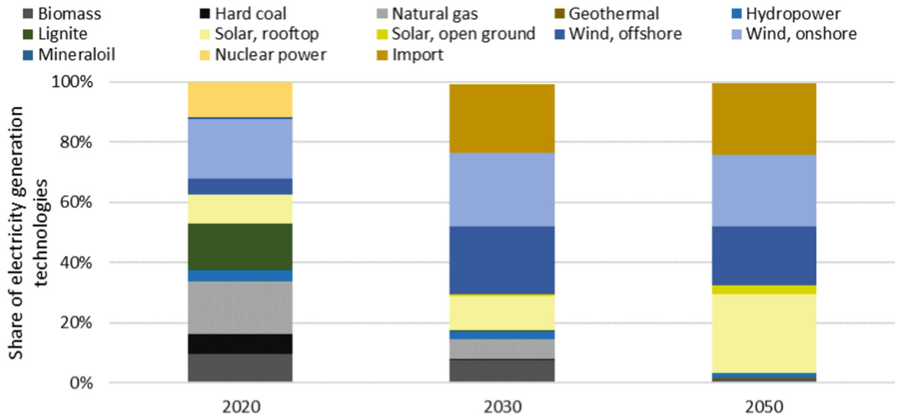

Fig. 5. Composition of the German electricity mix in different years [1]

from not requiring transportation, but also from oxygen as a by-product of electrolytic hydrogen production. Thus, only little additional oxygen needs to be produced for combustion by the air separation unit. As GHG emissions from electricity generation decline in the future, hydrogen heating of the glass trough becomes competitive with conventional natural gas heating from a climate perspective. Already in the 2030 scenario, hydrogen systems have a lower climate impact compared to an operation with natural gas. Hydrogen transport via LOHC is in close competition with the transport of liquid hydrogen. With the assumptions made here, LOHC transport today is more climate friendly than liquid hydrogen transport. However, with the assumed improvements for liquefying hydrogen and increasing the transport capacity of liquid hydrogen for the future scenarios, liquid hydrogen transport becomes minimally less GHG intensive in 2050. Taking into consideration the variability and uncertainty of the input parameters no clear recommendation between those two options can be given. In particular, transport distance, influences the results and for an actual implementation a more detailed analysis is recommended for these two options. The most climate-friendly option for the transport of hydrogen in the case of glass production is the use of pipelines because GHG emissions occur almost exclusively during initial and intermediate compression (pressure level max. 100 bar). Either new pipelines can be built for this purpose or existing natural gas pipelines can be converted. The construction of the in frastructure has a negligible effect.

The same trend as for Climate change can be observed for Fossil depletion. However, it becomes clear from Fig. 7 that this does not apply to all environmental impact categories. In particular, Metal depletion and Land use increase heavily when hydrogen heating is used.

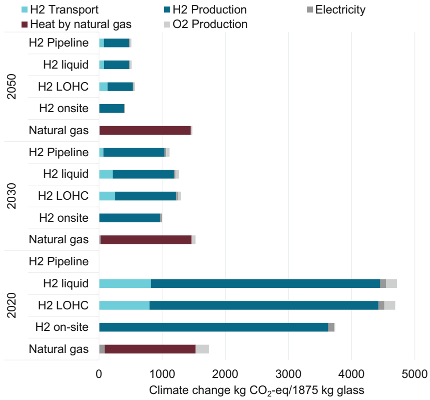

Fig. 6. Comparison of different heating options for specialty glass production regarding the impact category Climate change

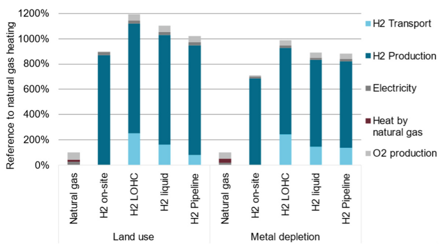

Fig. 7. Trade-offs for Land use and Metal depletion for specialty glass production (heating with natural gas as a reference) in 2050

This effect is largely related to the electricity-based hydrogen production. In addition, electricity is also required for conditioning the hydrogen for transport, i.e. liquefaction, (de)hydrogenation or compression.

In addition to Climate change and Fossil depletion, future on-site hydrogen production is the best alternative for the impacts of Photochemical ozone formation and Water depletion (Fig. 8). For Water depletion, low results can be achieved because almost all of the oxygen demand for oxyfuel combustion is met by the electrolysis which saves the water for cooling the air separation unit. In turn, the environmental impact of Photochemical ozone formation is lowered by the avoided truck transport, because the production and combustion of hydrogen cause less summer smog than the combustion of natural gas. For the Acidification and Particulate emissions categories, natural gas use remains the better options are not as pronounced as with Land use and Metal depletion.

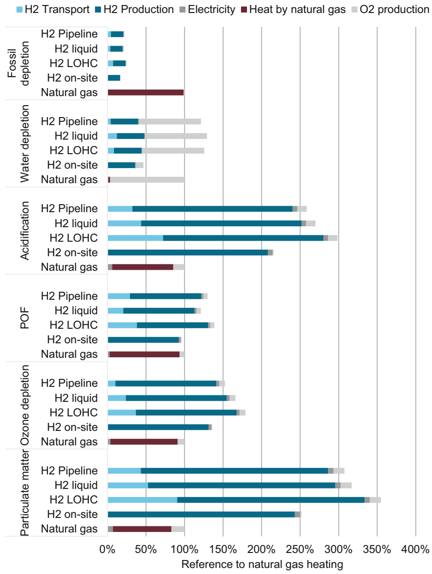

Fig. 8. Trade-offs of environmental impact categories for specialty glass production (heating with natural gas as a reference) in 2050; POF: Photochemical ozone formation

4 Conclusions

One challenge to slow down climate change is the defossilisation – mainly through electrification – of industrial processes. Hydrogen based solutions – often called Power-to-X – were identified to play an important role in this defossilisation process, especially when direct electrification is not possible. In this study it was shown that for the industrial specialty glass production in Germany a heating system with electrolytical hydrogen – even with hydrogen that is not green – is more climate friendly in 2030 and the years to follow than conventional natural gas heating. Taking the long investment cycles in the industry into consideration already today such systems must be further explored.

Regarding the different options for hydrogen supply from a climate perspective, on-site electrolysis is the best options. Not only the hydrogen from the PEM electrolyzer can be used, but also the simultaneously produced oxygen for the oxyfuel combustion. For production sites where this is not an option, several other options are available for the hydrogen supply, which are all more climate friendly than the natural gas heating. However, the results regarding Climate change for these options are within the range of the variability and uncertainty of the input data and for specific applications more detailed analyses are needed to define the most climate beneficial hydrogen supply option.

However, when looking beyond Climate change there are several trade-offs regarding other environmental impacts. The Land use, mainly for electricity generation, will be at least nine times higher than for the conventional natural gas system and the Metal depletion will be at least seven times higher. Further analyses are necessary to evaluate the sources of these high demands as well as their severity. In addition, measures need to be discussed to mitigate the impacts of Acidification, Ozone depletion and Particulate matter. Based on these deeper analyses it is advised to include further prospectivity aspects of the background system, for example for steel or cement production.

Before installing a hydrogen heating system, it should be checked if a direct electrification is another technically viable option or at least a hybrid system combining electric and hydrogen heating, because electric melting is always more efficient than hydrogen-based systems.

Acknowledgments. The authors gratefully acknowledge funding by the German Federal Ministry of Education and Research (BMBF) within the Kopernikus Project P2X: Exploration, validation and implementation of 'Power-to-X' concepts. Grant number: 3SFK2ZO-2. We thank the project partners from Schott AG, Hydrogenious LOHC Technologies GmbH and FZJ IEK-3 for their support in defining the product system. The paper is based on the study reported in the 4th Roadmap of the Kopernikus project "Power-to-X".

Authors' Contributions. Christina Wulf: Conceptualization, Methodology, Investigation, Formal Analysis, Writing - Original draft, Writing - Reviewing and Editing **Petra Zapp**: Conceptualization, Supervision, Funding, Writing – Reviewing and Editing

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