|  |  |
| --- | --- |
| cetlogo ***CHEMICAL ENGINEERING TRANSACTIONS*** ***VOL. xxx, 2025*** | A publication ofaidiclogo_grande |
| The Italian Associationof Chemical EngineeringOnline at www.cetjournal.it |
| Guest Editors: David Bogle, Flavio Manenti, Piero SalatinoCopyright © 2025, AIDIC Servizi S.r.l.**ISBN** 979-12-81206-21-2; **ISSN** 2283-9216 |

Hydrogen Safety in the Glass Industry: Focus on Electrolyzer Risks

Giulia Collinaa,b\*, Giulia Fedea, Marta Bucellic, Nicola Paltrinieria

a Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology NTNU, Richard Birkelands vei 2B, 7034 Trondheim, Norway

b Department of Civil, Chemical, Environmental and Materials Engineering, Alma Mater Studiorum - Università di Bologna, via Terracini 28, 40131 Bologna, Italy

c Department of Gas Technology, SINTEF Energy Research, Kolbjørn Hejes vei 1A, 7034 Trondheim, Norway

 giulia.collina@ntnu.no

Hydrogen is expected to penetrate economies and gain more and more interest from several sectors. The urgency of addressing climate change makes its capability to be carbon neutral very attractive. The glass sector, being energy-intensive, is eligible to be among the pioneers of new hydrogen applications, using it as a fuel in furnaces and replacing natural gas. However, introducing hydrogen in this sector involves technical changes due to the impacts on the process and the management of the plant: a thorough investigation of the main challenges of this implementation is needed. In addition, hydrogen has safety-critical properties; therefore, the new part of the plant responsible for hydrogen production and supply to the furnace introduces emerging risks to this sector, which is not familiar with hazardous substances. This study focuses on the safety implications of having green hydrogen production on-site and evaluates the impact of selecting a specific size of PEM electrolyzer through a consolidated approach based on Inherent Safety Key Performance Indicators.

* 1. Introduction

In 2023, the industry sector accounted for around 40% of total energy-related CO2 emissions, approximately 37.7 Gt (IEA, 2024). Several industrial sectors must find suitable solutions to modify and adapt their processes to meet the targets specified in the Paris Agreement. Energy-intensive industries are the hardest to decarbonize due to their heterogeneity, high cost-competitiveness, and sensitivity to product quality (Bataille et al., 2018). Melting the raw materials (sand, soda ash, limestone, and dolomite) for glass production requires temperatures above 1500 °C. In the current state, fossil fuels are the primary source of energy. Zier et al. (2021) outlined various decarbonization options regarding process intensification, waste heat recovery, recycling materials, and changing the fuel. Among everything, hydrogen stands out as one of the most attractive solutions, due to its CO2 neutrality.

The following subsections introduce relevant aspects that should be addressed within this transition: the effects on NOx emission, the impact on the glass quality, and the implication of using green hydrogen in terms of costs. The core of the present study focuses on safety aspects of using on-site produced green hydrogen through electrolysis.

* + 1. Effects on emissions

In addition to the carbon dioxide (CO2) emissions, glass manufacturing processes contribute significantly to nitrogen oxides (NOx) emissions, resulting from the oxidation of nitrogen in the combustion air, driven by high temperatures. Thus, switching to hydrogen-fueled glass furnaces helps reduce CO2 emissions, but may increase NOx emissions due to hydrogen’s higher adiabatic flame temperature. Additionally, two factors should be balanced: for the same amount of fuel, hydrogen combustion requires 75 % less oxygen, but a higher fuel demand is expected due to its lower volumetric energy density (3 KWh/Nm3 for hydrogen and 10 KWh/Nm3 for natural gas) (Luc Jarry, 2022). An efficient control system is crucial for monitoring NOx emissions accurately. Alternatively, oxyfuel melting furnaces eliminate this issue, as combustion occurs with pure oxygen, preventing the introduction of nitrogen.

* + 1. Impact on glass quality

The quality of the final product in the glass industry is crucial, given the specific requirements for transparency, durability, and resistance. The quality is highly sensitive to the furnace thermal conditions. Any variations in these factors can lead to bubble formation or other impurities, resulting in defects. Hydrogen changes the combustion conditions compared to natural gas, mainly due to its higher laminar speed, higher adiabatic flame temperature, different flame length, and lower visibility. Additionally, since water is the only product of hydrogen combustion, a higher level of steam is produced, which can lead to foam formation, resulting in bubbles and voids in the molten glass. Lastly, hydrogen can negatively impact the integrity of refractories, which are essential materials that resist high temperatures and corrosion within the furnace.

* + 1. Implications of using green hydrogen

Fuel switching in glass manufacturing only supports decarbonization if hydrogen is produced with low emissions. Green hydrogen from renewable-powered electrolysis is the most sustainable choice. Simulations (Gärtner et al., 2021) show that non-renewable-powered electrolysis can double CO₂ emissions. However, high costs and renewable energy variability are key challenges. Policy incentives and larger electrolyzer deployment can reduce costs (IEA, 2023). The variability of renewable energy sources introduces fluctuations in green hydrogen production (Groenemans et al., 2022), leading to potential fuel shortages or surpluses in glass manufacturing. Ensuring a stable and continuous energy supply is crucial, as variations of the heat input can compromise glass quality.

* + 1. Safety aspects

One of the bottlenecks of rolling out hydrogen-based technology is the critical safety properties of hydrogen. As of now, the glass industry handles only the raw materials required for glass production: sand (or silica, SiO2), soda ash (Na2CO3), limestone (CaCO3), and a small amount of dolomite (MgCa(CO3)2). The furnace is fed by natural gas, which is not accountable for the stored substances because it is directly taken from the gas network. Introducing hydrogen in the plant requires installing new equipment to produce, store and transport hydrogen to the burners. The glass sector is only familiar with occupational risk aspects, mainly due to high-temperature work environments that could generate physiological strain or thermal burns (International Labour Office, 2011). Other aspects are general ergonomic stressors, noise, the possibility of inhalation of airborne particulate matter from raw materials, and contact with sharp glass.

The willingness to implement hydrogen in the furnace significantly changes the safety management. Hydrogen has a wide flammability range (4 % - 75 %), a low ignition energy (0.017 mJ), and a small molecular size which increase the likelihood of leaks (Ustolin, 2020).

The possibility of introducing hydrogen in this sector is still in the feasibility stage; only a few pilot projects are investigating this switch (HyNet North West, 2020), (H2GLASS, 2023), (HyGlass, 2020). Implementing Inherently Safer Design practices is widely regarded as the most cost-effective approach to address safety issues in the early stages of process design, aiming to eliminate or minimize process hazards as much as possible (Kletz, 2010). Therefore, this study compares the safety implications of choosing a specific size of electrolyzer through a consequence-based Key Performance Indicators (KPIs) approach (Tugnoli et al., 2007). The focus is on PEM electrolyzers due to their better coupling with renewable energy (Park et al., 2025).

* 1. Methodology

Figure 1 shows the methodology adopted in the present study. Before adopting an inherent safety approach to compare different sizes of electrolysis systems (Step 1-3), a few preliminary preparation steps are required (Step 0).

*Step 0: Preliminary steps*

The green hydrogen production through electrolysis requires the PEM electrolysis stack and the corresponding Balance of Plant (BoP), including water purification stage, power electronics, oxygen purification loop, control and safety systems to regulate operational conditions, and the hydrogen purification stage (Smolinka et al., 2015). The potentially hazardous equipment in the system are the electrolysis stack and the hydrogen-water separator. Depending on the overall power rating, the electrolyzer unit comprises one or more PEM stacks. PEM stacks available commercially have standardized capacity, and specifically 0.5 MW, 1 MW, 1.25 MW and 2.5 MW. The electrolysis stack is not listed among the equipment of the general safety guidelines (TNO, 2005). The following steps require a reference component to evaluate the Inherent Safety performance. Hence, the electrolysis stack is associated with a vessel which is the most suitable in the list.



Figure 1: Flow chart of the methodology applied in this study.

Table 1 shows the reference online from the Bosh PEM stack of 1.25 MW.

Given the limited publicly available information about the detailed specifications of different sizes electrolysis systems, the stack volumes for different electrolyzer capacity are calculated by scaling the reference dimensions of the 1.25 MW PEM stack from Bosh.

The residence time (τ) in the electrolysis stack to allow the reaction is considered the scaling parameter. It is defined as the ratio of the equipment volume and the inlet flow rate. Similarly, the volume of the hydrogen-water separator is assessed from known data from an existing system and adapted based on the different hydrogen production. However, one of the advantages of the PEM electrolyzer is the high purity of hydrogen, meaning that the stream exiting the stack is already very rich in H2, and the equipment for the separation is generally small.

Table 1: Dimension of commercial Bosh PEM stack of 1.25 MW.

|  |  |  |
| --- | --- | --- |
| Dimension | Unit | Value |
| Width | m | 0.8 |
| Length | m | 0.97 |
| Height | m | 1.5 |
| Volume | m3 | 1.16 |

*Step 1-3: Inherent Safety KPIs calculation*

Once the foundational data is collected, the Inherent Safety (IS) KPI developed by Tugnoli (2007) approach can be applied. Step 1 involves identifying Loss of Containment (LOC) events: 10 mm leak (LOC 1), continuous 10 min leak (LOC 2) and catastrophic rupture (LCO 3) (TNO, 2005). Each event $j$ is simulated through the software PHAST 8.9 by DNV to evaluate the damage distances for the Release Accident Scenarios (RASs), as in Step 2a. According to Tugnoli et al. (2007), the threshold values to evaluate the damage distances are: 14 kPa for the Vapor cloud Explosion, 7 kW/m2 for the fireball and flashfire, and ½ LFL (low flammability level) for the flashfire. The effects are evaluated at 1 m height from the ground level and the following environmental condition is considered: average wind speed of 1.5 m/s, Pasquill category F, meaning night time, air temperature of 25 °C with 70 % of relative humidity, and surface temperature of 10 °C. In parallel, to represent the yearly occurrence in Step 2b, credit factors for each LOC are selected from the literature, considering the electrolysis stack as a process vessel and the hydrogen-water separator as a pressure vessel (TNO, 2005). The software does not allow simulating hazardous inventories less than 0.5 kg; therefore, the H2-water separator is part of the analysis only for the highest green hydrogen production options.

Step 3 focuses on the evaluation of IS-KPIs hazard indexing. The Unit Potential Hazard Index (UPI) is calculated as in Eq(1) to quantify the maximum potential damage generated by the worst-case scenario. $h\_{j} $is the maximum distance for the $j$ LOC among the different RASs and $n$ is the number of stacks in the module.

|  |  |
| --- | --- |
|  $UPI=n∙\max\_{j}\left(h\_{j}^{2}\right)$ | (1) |

The Unit Inherent Hazard Index (UHI) is determined as in Eq(2), incorporating the assigned credit factors to reflect the risk of the equipment.

|  |  |
| --- | --- |
| $UHI= n∙\sum\_{j}^{LOC}C\_{f\_{j}}∙ h\_{j}^{2}$ | (2) |

For the greater hydrogen production, the IS-KPIs are the inherent Hazard Index (HI) and the Potential hazard Index (PI), calculated as the sum of the unit indexes of the electrolysis stack and the separator. The effect of considering also the separator is highlighted comparing the overall HI with the UHI of the electrolysis stack (ES) and the overall PI with the UPI of the electrolysis stack (ES).

* 1. Results and discussion

Different sizes of electrolyzers are selected as possible options to feed the glass furnaces with green hydrogen produced on site, depending on the size of the plant. Table 2 shows the details, highlighting the hydrogen nominal production and the composition of the module, in terms of number and type of stacks. The 10 MW system is considered in two different combinations, since different information was found on the manufacturers’ website, and specifically as either four stacks of 2.5 MW and eight stacks of 1.25 MW.

Table 2: Details of different sizes of electrolyzer. (\*) Different indications are available on the electrolyzer manufacturers' website.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Power rated [MW] | H2 production [Nm3/h] | H2 production [kg/h] | Nr. of stacks ($n$) | Stack power rated [MW] |
| 0.5 | 100 | 9 | 1 | 0.5 |
| 1 | 200 | 18 | 1 | 1 |
| 1.25 | 250 | 23 | 1 | 1.25 |
| 2 | 400 | 36 | 2 | 1 |
| 2.5 | 500 | 45 | 1 | 2.5 |
| 3 | 600 | 54 | 3 | 1 |
| 5 | 1000 | 90 | 4 | 1.25 |
| 10 (\*) | 2000 | 180 | 8 | 1.25 |
| 10 (\*) | 2000 | 180 | 4 | 2.5 |
| 20 | 4000 | 360 | 8 | 2.5 |

Table 3 summarizes the dimension for each reference stack calculated from the available information for the 1.25 MW. These values serve as input for the simulation in the software and for calculating the damage distances, since the stack is considered a process vessel. In this study, the worst results are attributable to fireballs and Vapor Cloud Explosions (VCE) resulting from LOC 1 and LOC 3. The accident scenarios generated from LOC 2 are not particularly critical in this study.

Table 3: Electrolyzer stack dimensions based on residence time.

|  |  |  |
| --- | --- | --- |
| Residence time (s) | Reference stack capacity [MW] | Volume [m3] |
| 17 | 0.5 | 0.8 |
| 1 | 0.9 |
| 1.25 | 1.1 |
| 2.5 | 1.8 |

Figure 2 shows the results of the IS-KPIs for the considered equipment. It is essential to first consider the baseline cases in Table 3, which have a single stack (0.5 MW, 1 MW, 1.25 MW, 2.5 MW). The indexes UPI and UHI naturally increase as more hydrogen is produced. This trend is expected since a system with one stack has a direct proportional relationship between its size and the amount of hydrogen generated, impacting the safety performance accordingly. The results clearly show that, according to this methodology, the inherent safety performance of an electrolyzer is more influenced by the number of stacks than by the amount of hydrogen produced. Indeed, comparing the results of the 2 MW and 2.5 MW electrolyzers, the impact of having an additional cell is evident in the 2 MW case. The UHI increases because an additional cell is introduced and the likelihood of something going wrong inherently increases due to the presence of more components susceptible to failure. The UPI considers the worst-case scenario, which represents the simultaneous faults. Even more pronounced is the comparison between the two 10 MW modules. Reducing the number of stacks is inherently safer for the same amount of hydrogen production. A configuration with fewer stacks delivering the same hydrogen output is inherently safer, as it reduces the number of interfaces, failure points, and potential for fault propagation. Therefore, from a safety perspective, minimizing the number of stacks while maintaining production levels is a favorable design strategy across different plant scales and applications.

Figure 2: Inherent safety KPIs for different sizes of electrolyzer.

Figure 3 shows the effect of the separator vessel. The UPI and UHI of the electrolysis stacks are compared to the overall PI and HI of the electrolysis systems. The labels represent the percentage increase compared to the case without the separator. Even if there is an impact, the change is not high enough to be decisive when selecting between different electrolyzer capacities.

Figure 3: Impact of hydrogen-water separator on the inherent safety KPIs of the electrolyzer system.

Generally, the results strictly depend on the failure frequency considered as explained in the methodology section. Therefore, performing a sensitivity analysis could be beneficial to assess how variations affect the outcomes. Additionally, refining the evaluation of the credit factors which impact the UHI could further improve the robustness of the analysis. In this study, the stack is modeled as a process vessels, applying the conventional credit factors for this reference equipment. However, developing tailored credit factors would lead to more accurate estimation of the inherent safety performance.

* 1. Conclusions

The transition towards hydrogen as a fuel in the glass industry represents a promising pathway to decarbonize one of the most energy-intensive sectors. However, this study showed that this transition presents several challenges regarding emissions, product quality, cost, and safety, especially if the on-site green hydrogen production is selected. Hence, in this study the inherent safety assessment of different PEM electrolyzer sizes has been conducted using the Inherent Safety Key Performance Indicator approach. The lack of public data availability makes modelling the system more challenging; indeed, a scaling up approach based on the residence time has been adopted. As expected, the results show that increasing hydrogen production generally leads to lower inherent safety performance. Still, the number of cell stacks significantly impacts the overall safety performance, mainly because it affects the potential failures. In addition, while the hydrogen-water separator does impact safety indexes, its effect is not substantial enough to be a decisive factor in electrolyzer selection. This approach could be extended to the entire hydrogen-dedicated section of a decarbonized glass plant, optimizing the design phase with a strong focus on safety.

Acknowledgments

This work has received fundings from the European Union Horizon 2020 research and innovation program under the Grant Agreement No. 101092153. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or European Health and Digital Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

References

Bataille C., Åhman M., Neuhoff K., Nilsson L.J.,Fischedick M., Lechtenböhmer S., Solano-Rodriquez B., Denis-Ryan A., Stiebert S., Waisman H., Sartor O., Rahbar S., 2018, A review of technology and policy deep decarbonisation pathway options for making energy-intensive industry production consistent with the Paris Agreement, Journal of Cleaner Production, 1887, 960-973.

Gärtner S., Rank D., Heberl M., Gaderer M., Dawoud B., Haumer A., Sterner M, 2021, Simulation and Techno-Economic Analysis of a Power-to-Hydrogen Process for Oxyfuel Glass Melting, Energies, 14, 24.

Groenemans H., Saur G., Mittelsteadt C., Lattimer J., Xu H., 2022, Techno-economic analysis of offshore wind PEM water electrolysis for H2 production, Current Opinion in Chemical Engineering, 37, 100828.

HyNet North West, 2020, Unlocking a low carbon future.

H2Glass, 2023, Decarbonising our future.

IEA, 2023, Global Hydrogen Review 2023.

IEA, 2024, World Energy Outlook 2024.

International Labour Office, 2011, Encyclopedia of Occupational Health and Safety, XIII, 84

Kletz T. A., Amyotte P., 2010, Process plants: a handbook for inherently safer design, Second Edition, CRC Press.

Luc Jarry, 2022, Hydrogen combustion technologies for a smooth transition, 26th International Congress on Glass.

Park J., Kang S., Kim S., Kim H., Cho H. S., Lee J.H., 2025, Comparative techno-economic evaluation of alkaline and proton exchange membrane electrolysis for hydrogen production amidst renewable energy source volatility, Energy Conversion and Management 325, 119423.

Smolinka T., Ojong E.T., Garche J., 2015, Chapter 8 - Hydrogen Production from Renewable Energies—Electrolyzer Technologies, in: Moseley, P.T., Garche, J. (Eds.), Electrochemical Energy Storage for Renewable Sources and Grid Balancing. Elsevier, 103–128

TNO, 2005, Purple Book - Guidelines for quantitative risk assessment.

Tugnoli A., Cozzani V., Landucci G., 2007, A consequence based approach to the quantitative assessment of inherent safety, AIChE Journal 53, 3171–3182.

Ustolin F., Paltrinieri N., Berto F., 2020, Loss of integrity of hydrogen technologies: A critical review, International Journal of Hydrogen Energy 45, 23809–23840.

Zier M., Stenzel P., Kotzur L., Stolten, D., 2021, A review of decarbonisation options for the glass industry. Energy Conversion and Management: X, 10, 100083.