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Key Factors To Integrate Hydrogen For The Glass Manufacturing Industry.

Paul K. Wan[a]*, Chiara Caccamo[b], Ernesto Cattaneo[c] Xabier Lekube[d], Marta Bucelli[b], Giuseppe Fragapane[a]

[a]SINTEF Manufacturing, Trondheim, 7036, Norway
[b]SINTEF Energy Research, Trondheim, 7036, Norway
[b] Stara Glass,Genoa, 16129, Italy
[b]Sener Energy, Bilbao, E-28760, Spain

* Corresponding author. Tel.: +47 93 98 46 04. *E-mail address:* paul.wan@sintef.no

Abstract

Glass industries contribute approximately 22 million tonnes of CO2 emissions in Europe annually. The European Clean Hydrogen Alliance has developed an investment agenda to support the strategic investment of hydrogen amounting to 9.3 billion €. Hydrogen is a potential fuel source but is not readily available in nature for direct combustion. Pure hydrogen can be synthesised by electrolyser to produce hydrogen. To ensure the success of transitioning the glass industry to using hydrogen, there are several factors to consider apart from the cost of electrolyser. Most of the publication focuses mainly on the efficiency, cost and the direct application of the electrolyser in Europe. However, there is a gap in empirical studies that provide challenges and needs with the use of hydrogen in glass manufacturers. In this work, we aim to key factors to provide new insights regarding the adoption of hydrogen in the manufacturing sector. The case study was carried out with 4 European glass manufacturers that plan to use hydrogen as a fuel or have tested it on small scales. Workshops were organized with experts from different fields for solution development. All 4 glass manufacturers have an objective to reduce GHG emissions and explore the use of H_2 to replace natural gas but lack the knowledge in the management, particularly the safety aspects, of H_2 in furnaces. Factors such as the safety of hydrogen, required furnace modifications and the development of smart production management should be focused on integrating hydrogen into the glass manufacturing industry. One challenge is that the available data are mostly on the combustion of natural gas and not from hydrogen making development prediction using digital twins challenging. This insight could also contribute to the replicability of the developed solutions for other industries like aluminium and cement.

Keywords: Hydrogen, factors, glass industry, manufacturing, case study

1. Introduction

Glass is a common material found in buildings, photovoltaic panels, containers and medicals devices. With the increasing population, the demand for glass is also rising. Today, glass production industries contributes substantially to CO_2 emissions with approximately 95 million tonnes globally and 22 million tonnes in Europe annually [1]. Natural gas is the main type of fuel source in furnaces to melt raw materials at a temperature of around 1600ºC to molten glass for shape formation. In the last decade, glass furnace emissions, the main GHG contributor, have remained quite stable at approximately 18 Mt CO2eq due to the energy efficiency of a furnace having reached the limit [2]. To support the decarbonisation process, hydrogen can be an alternative fuel source to reduce carbon emissions during the melting process in furnaces [2]. Most importantly, Europe can reduce its dependence on important fossil fuels from third countries [3] .

Hydrogen has emerged as an alternative for natural gas in combustion process in glass production [4]. One key advantage is that it can enable higher furnace throughput (higher tonne of glass produced a day) due to high specific

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energy content while reducing GHG emissions [5]. From a production point of view, hydrogen can blend with natural gas easily [6] and be used in existing furnaces which are designed for natural gas combustion The integration may result in a less negative impact on the furnace's lifetime.

Unlike natural gas, hydrogen is not readily available in nature to be used as fuel for direct combustion [7]. Pure hydrogen can be synthesised by electrolyser to produce hydrogen with little impurities [8]. The commercially available electrolysers in the market are alkaline electrolyser (ALK), anion exchange membrane electrolyser (AEM), and proton exchange membrane electrolyser (PEM) [9] but they are costly for some manufacturers to bear.

The European Clean Hydrogen Alliance has developed an investment agenda to stimulate the rollout of hydrogen production and support the strategic investment of hydrogen amounting to 9.3 billion € [10]. To ensure the success of transitioning the glass industry to using hydrogen, there are several factors to consider in addition to cost. At present, the publications focus mainly on the efficiency, cost and the direct application of the H_2 electrolyser. There is also a gap in empirical studies that provide challenges with the use of hydrogen in glass manufacturers that plan to use hydrogen as a fuel or have tested and verified on small scales. In this work, we aim to present the initial result and lessons learned by looking at the implementation and operation of H_2 electrolyser using a case study.

The rest of the paper is organised as follows: Section 2 reviews the existing literature on factors to adopting hydrogen from electrolyser. Section 3 explained the methods used and the data collected in this study. The next section describes and summarises the challenges faced by the 4 cases. Section 5 explains the solution to overcome the challenges based on the use cases. We discussed the critical factors in section 6 and concluded in section 7.

2. Background

Hydrogen production using electrolyser is now more available and feasible mainly due to the significant development of electrolyser technology and a more economical production cost [11,12]. It is a greener option compared to natural gas during glass production. However, there are some critical factors like safety aspects of the plant, operators and the regions that need to be addressed [13] .

[13,14] have highlighted that different safety factors need to be considered since hydrogen is categorized as a hazardous substance with a wide flammability and detonability range of 4 – 75 %vol and 13 – 59 %vol in air, respectively [15]. Furthermore, hydrogen is characterized by a minimum ignition energy of 0.019 mJ, which is 10 times lower than the one of methane [16]. Undetected hydrogen leaks, ignited by any undesirable ignition source can result in a fire and/or explosion with significant consequences to humans, assets and the environment. Detecting hydrogen leaks represents a technological challenge due to its physical properties. Hydrogen gas is colourless, odourless, and tasteless. [17] suggested adopting the Risk-Based Maintenance methodology along with changes in maintenance and inspection policies could be the solution to enhance the safety and reliability during the use of H_2 during the melting process.

Another factor to be considered is the furnace in the melting of raw material is the critical step in glass production which results in the highest GHG emission. Currently, most of the furnaces including hybrid furnaces are designed for natural gas and not hydrogen. Since hydrogen has many unique properties such as a wider flammability range, higher flame speed, and lower heating value on a volume basis, to many fuels like natural gas, there are some furnace modification and design considerations with the use of hydrogen [18]. For example, the fuel injectors may need to be larger when using high hydrogen fuels but retrofits depend on the types and design of the existing ceramic burner blocks [18].

Flame detection is also a factor to consider when using hydrogen. Since the flame is also weaker with the naked eye and odorless, [19] stresses on additional engineering control are needed to understand the behaviour of the flame in the furnace during the melting process to ensure safe use. [20] suggests a simulation-based computational fluid dynamics (CFDs) can be used for modelling hydrogen dispersion release, dispersion, radiation, fires, and explosions.

Digital solutions such as digital twins offer a new opportunity to effectively face these problems by improving online control and providing fault detection, diagnosis, and prediction services. The available electrolysers in the market such as ALK and PEM [9] still face limitations such as high energy consumption with a short service life [14,21]. [22] developed guidelines for designing a Digital Twin for a hydrogen production system. For example, [22] suggested important steps like defining the physical system and mathematical modelling of the relationships between operational parameters and the effects of these on performance and lifetime are crucial for development.

Currently, there is a lack of empirical studies that provide insights such as the needs and challenges of glass manufacturers that plan to use hydrogen as a fuel or have tested and verified on small scales. Other factors such as safety concerns due to the hydrogen properties and infrastructure development are some other important factors to consider. These factors need to be considered to facilitate the decarbonization journey. Also, there is a need for potential solutions to address the challenges to accelerate the adoption of hydrogen in production.

3. Methods and data collection

The case study was conducted to achieve the current study's aims and provide new insights regarding the adoption of hydrogen in the manufacturing sector. This research approach is suitable for investigating a real-life phenomenon when the associated variables and complexity are not sufficiently understood [23]. The case study research method has been highly recommended by many researchers as an excellent tool for improving the conceptual and descriptive understanding of phenomena [24–26].

The case study was carried out with 4 glass manufacturers in Europe and is summarized below:

Manufacturer A: produces container glass for spirit and perfume bottles with 3 production lines. They have 2 furnaces in production and at least 1 of the furnaces will be tested with H_2.

Manufacturer B: produces container glass for bottles with 2 production lines with 5 different forming machines to form the shapes. They have 2 furnaces in production and only 1 of the furnaces will be tested with H_2. Natural gas and electricity are the power sources.

Manufacturer C: produces container glasses targeting cosmetic & perfumery and food & beverage. They have 2 batch-charger machines at the side of the furnace. Only one of the furnaces will be tested with H_2.

Manufacturer D: produces 2 two production lines and manufactures 2 types of fiberglass (e.g continuous or chopped fiberglass). They have 1 furnace which runs natural gas.

Three container glass manufacturers (A, B & C) are selected to better to generalize a conclusion for glass manufacturers. The fiber glass manufacturer is to validate if the result is transferable to different types of glass manufacturers. The 4 glass manufacturers cover a wide target market ranging from construction to perfume and beverage bottles. They have employees between 200-2000 and produce between 60,000 to 1,100,000,000 glasses each year.

These glass manufacturers have common goals in contributing towards decarbonization through an EU Project. Empirical data was collected through a series of questionnaires, online workshops, field visits, and information retrieved from field documents. Various workshops were carried out focusing on three aspects of the installation of electrolyser which are: (1) furnace modification, (2) smart production management and (3) safety management. In addition to that, we organized focus groups to further discuss with experts from the electrolyser, furnace, and safety sectors for solution development.

4. Mapping the challenges of H_2 case

All these 4 glass manufacturers aim to reduce GHG emissions and explore the use of H_2 to replace natural gas during the combustion process. They lack the knowledge in management of H_2 in furnaces as they are all built and designed for natural gas. For example, all 4 manufacturers are uncertain how hydrogen combustion would have an impact on the refractors and the lifetime of the furnace.

Manufacturers C and D also pointed out that they lack the knowledge about the thermodynamic conditions such as temperature distribution, foam level, and furnace stability, with the use of hydrogen combustion because this could have an impact of the product quality. Most of the manufacturers are expecting some modifications to the furnace for H_2 integration.

All 4 manufacturers also highlighted that they lack knowledge of H_2 safety operation conditions and the safety

Table 1. A summary of the cases highlighting the challenges and needs

Challenges	A	B	C	D
Furnace				
H2 combustion	Lack of knowledge of the effect of the glass-melting process	Requires more testing of H2 combustion	Lack of knowledge of the thermodynamic conditions	Lack of knowledge of the thermodynamic conditions
Furnace readiness	Not applicable	Verify if modifications in the furnace layout are needed	May require modification to integrate with H2	May require modification to integrate with H2
Production quality	Lack of knowledge of the effect of hydrogen combustion on the glass melting process and furnace.	Verify the impact of Hydrogen combustion on the glass quality	Not applicable	Lack of knowledge of the potential impact on the furnace
Safety				
Explosion protection systems provider:	Not applicable	Not applicable	Not applicable	Not applicable
Safety operation	Lacks the knowledge of H2 conditions	Lacks control system over safety issues	Lacks the knowledge of H2 conditions	Lacks control system over safety issues
Personal readiness	Operators have little to no experience in H2 operation	Not applicable	Not applicable	Not applicable
IT Infrastructure				
IT Readiness	No established automated protocol for furnace operation control	Not applicable	increase know-how about the H2 technology integration in our installed equipment.	Not applicable
Information and data availability	Data generated from H2 is very limited.	Not applicable	Not mentioned	Not applicable
H2 flame visibility	Only have cameras for natural gas	Lack of knowledge of the suitable types of equipment for flam check	Reduce visibility making it difficult to manage.	Lack of knowledge equipment to visualize H2 flame

control system for H_2 . Manufacturer A highlighted that current operators and other personnel have little to no experience in H_2 operation. All the manufacturers also pointed out another challenge is the visibility of H_2 flame is weak which makes management of the flame more difficult compared to flame from natural gas.

Manufacturers B and D did not mention much on the IT infrastructure because they have different priorities and different technological maturity compared to use cases. Manufacturers A and C pointed there is a need to establish an automated protocol for furnace operation control and to increase know-how about the H2 technology integration in our installed equipment. A summary of the cases highlighting the challenges and needs is shown in Table 1.

5. Derived solutions to overcome the challenges.

This section explains the derived solutions to overcome the challenges presented by use cases.

5.1. Safety of hydrogen

Since hydrogen is a substance classified as hazardous due to its flammability and explosivity, the use of hydrogen would require on-site adjustments and precautions to avoid any possible accident potentially leading to injuries and casualties of people working, as well as infrastructure and equipment damages. The priority is to ensure quick detection and reaction when hydrogen leaks occur.

Equipment design solutions to prevent leakages of hydrogen gas must also be considered. For example, the number of flanged connections shall be reduced to a minimum as they are weak points which are prone to hydrogen leakage. In addition to that, the materials used for piping, storage tanks and all the other pieces of equipment must be suitable for operations in the presence of hydrogen. Compatible materials like stainless steel should be used because of their resistant properties towards hydrogen embrittlement and other degradation phenomena such as high-temperature hydrogen attack.

The sensing techniques should be developed to optimize rapid leakage detection which stops the operations in case of loss of hydrogen containment. Automatic hydrogen gas detection can be implemented on all the pipelines upstream which feed hydrogen to the furnace approximately. Flame and temperature detectors can be installed at the hydrogen electrolyser container and internal locations of glass manufacturers. In case of fire at the furnace or the glass production building, the hydrogen supply from the electrolyser and/or the container systems must be stopped, and safety released to the atmosphere as a preventive measure.

Maintenance and inspection of the system with a detailed checklist before, during and after the use of hydrogen needs to be developed to ensure the integrity of the material and equipment. For example, an operator equipped with hydrogen gas detectors should check the area at regular time intervals. The emergency shutdown will be initiated, and the designated valves will be closed if hydrogen gas is detected at the furnace or the rest of the equipment at the technological stack. This is to reduce the amount of hydrogen released and other potential consequences.

An emergency response and isolation procedure should be developed to ensure the containment of hydrogen once a leak is detected during the testing or operation of hydrogen for production. The monitoring of the equipment and a reliable gas detection system would be installed, as shown, to detect potential leaks. Once a leak is detected, the emergency response and isolation procedure will be activated. A dedicated emergency response plan and a team with trained personnel must be developed to ensure timely action of firefighting in case of an accident.

5.2. Required furnace modifications.

Furnaces of all the use cases are designed with the use of natural gas. The expert suggested some of the furnace features require some modification to increase the efficiency of using H2 in the furnace and this matches with the suggestion [18]. For example, it is expected that the burner blocks of the furnaces be larger and the diameters to be adjusted. These changes must be kept during the port and superstructure design. Other features such as the port geometry may require some modifications. For example, it needs to be evaluated if it is useful to distribute the regenerative gas injectors in alternative positions, to optimize both the reduced flame length and to arrange a staged combustion, which is expected to emit a lower level of NOx.

An increase in NOx production is also expected with the use of H2 and the glass industry has been facing its NOx issues for almost two decades now. The two common types of filters used in glass production are bag filters and electrostatic precipitator (ESP) filters. These solutions do not affect NOx containment, other filters such as the candle ceramic filter can also be used. This technology is more cost-effective in the long run. New measures or modifications need to be considered, if the NOx level emission is higher than expected, both in terms of the correct development of our tests and as a design reference for future furnaces.

It is important to take note that not all the features are expected to change to meet the H_2 criteria. Other features of the furnace such as the barrage, batch charger and tuckstones are also not expected to change to meet the H_2 criteria. However, testing and experiments must be conducted to ensure the expectations are met and solutions will reach and maintain quality glass production. For example, the bottom of the furnace is expected to have no change but during hydrogen testing in manufacturer A, the bottom temperature of the melted glass in the furnace dropped more with hydrogen than with natural gas. Therefore, additional heaters at the bottoms may be needed to maintain the temperature will be monitored by furnace thermocouples.

5.3. Smart production management

The development and deployment of smart production process solutions depend on the availability of data and the level of digitalization of the manufacturer. Therefore, data architecture and big-data infrastructure of the furnace and final product should be a key focus. This can help to predict the furnace's behaviour with the use of hydrogen as well as to understand the impact on the final product quality. For example, on-site data acquisition and cloud communication should be established based on pre-existing industrial data and new data related to innovative hydrogen technology. In addition, the definition of standards and protocols should also be developed to access, manage and exchange data.

The focus on developing digital twin solutions and automation control systems, including predictive maintenance and smart production planning and control digital twins should also be considered when it comes to the use of hydrogen. For example, digital Twins for predictive maintenance operations and scheduling Digital Twins with 2 models. The first is with predictive models based on existing models (reduced order modelling, transfer learning for data drive models) and the second with the Prescriptive model as the second layer of models based on foreseeing behavior of target processes to assert corrective actions.

Assessment of hydrogen impacts on product quality by assessing the thermodynamic behaviour of hydrogen mix and its effect on downstream processes is important to ensure the quality of glass remains the same as the use of hydrogen. The furnace process conditions (e.g surface temperature characteristics, flame measurement) should also be assessed as they have a direct impact on the final glass quality. Sensors and the installation of infrared cameras along with optimization models can be designed to help to detect flames in a furnace when using hydrogen gas.

6. Discussion

From the literature [15] and this case study, safety is a key factor when it comes to the integration of hydrogen for manufacturers considering transitioning towards hydrogen with electrolyser [20]. All the use cases lack knowledge of H_2 safety operation conditions and lack emergency response if there is a leak of hydrogen. In addition, to developing and implementing different safety measurements such as using or replacing piping with materials like costly stainless steel, the manufacturer needs to also consider the sufficient space for electrolysers for hydrogen production, re-skilling of operators, storage facilities, and hydrogen refuelling stations for transport needs to be considered. As of now, [14] highlighted that there is no existing framework for selecting the right technology for safety aspects.

Development of smart solutions such as the digital twins' model for predictive maintenance operations and scheduling can help to prolong the lifespan of the electrolyser is another critical factor. However, as of now, based on the current literature analysis done by [22] shows that actual implementations of digital twin for operating electrolyser systems are rare and depend on the data available. In addition to that, the available historical data highlighted by the use cases are mostly the combustion of natural gas and not hydrogen. To enable the development of smart solutions, additional work focusing on both the physical layer (e.g new sensors on the furnace) and the digital layer instead of solely relying on simulation data or historical data from operational plants are needed for a more accurate prediction with the digital twins.

The energy source for hydrogen production is also another factor to consider. The 4 case studies aim to reduce GHG emissions with hydrogen, but the type of hydrogen is not mentioned. For example, grey hydrogen is the production of natural gas or coal. With the use of grey hydrogen, the environmental impact needs to be considered. Green hydrogen, where the production of H_2 is from renewable sources such as solar and wind can be unstable. For example, in events of low to no availability of electricity from offshore wind, the electrolyser needs to be supplied with backup power to ensure continuous operation. Completely shutting off and turning on the electrolyser can lead to safety issues related to gas crossover and heat management [27].

Apart from hydrogen, biogas can also be used as an alternative for heat and power can also displace the use of fossil fuels and thus reduce GHG emissions and other pollution [28]. However, one of the main problems is the fluctuating compositions, which are undesirable from a glass manufacturer's point of view [29]. Unexpected and undesirable gas fluctuations can lead to problems in production as well as increased pollutant emissions such as NOx. Nonetheless, future studies in using biogas for combustions should be explored.

7. Conclusion

The development of H2 infrastructures in various industrialized countries is becoming increasingly likely so relatively low costs can be expected in the future. However, factors like safety measures such as re-skilling of operators, infrastructure development for the use of H2, and some modifications to the furnace need to be considered in the overall deployment of H2 combustion of the furnace glass sector. Another critical factor to consider is the data availability of hydrogen combustion for smart system development. This paper aims to cover different types of glass products, and to distinguish the critical factors common to all processes from those specific to each production. The result could also contribute to the replicability of the developed solutions for other hard-to-abate industries like aluminium and cement.

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