Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 59-10 (2025) 178–183

A model-based approach to hydrogen supply scenarios for decarbonizing the glass melting process

Giulia Fede*, Fabio Sgarbossa*, Daniel F. Silva**, Giulia Collina*

*Department of Mechanical and Industrial Engineering, Faculty of Engineering, Norwegian University of Science and Technology NTNU, Trondheim, Norway
**Department of Industrial and Systems Engineering, Auburn University, Auburn, AL 36849, USA

Abstract: Hydrogen is expected to be critical in decarbonizing energy-intensive industries, including the glass sector. Replacing natural gas with hydrogen as a combustion fuel in the melting process offers significant environmental advantages by eliminating direct CO_2 emissions. However, hydrogen adoption faces challenges, including the lack of hydrogen-related infrastructure in glass manufacturing plants. This paper introduces an approach for modeling the hydrogen supply to the glass melting furnace to help glass manufacturers evaluate the economic and environmental impacts and the required infrastructure for this transition. The study explores on-site hydrogen production via water electrolysis and external hydrogen supply by trucks and demonstrates its application through a case study. The model relies solely on long-term aggregated data, making it easily applicable and modifiable. While hydrogen integration reduces direct CO_2 emissions, results show that its overall impact depends on its production method. Additionally, policy incentives and electricity sources strongly influence its economic viability.

Keywords: hydrogen, cost model, hydrogen system design, decarbonization, glass industry

1. INTRODUCTION

Achieving the European Union's net-zero emissions target by 2050 requires substantial decarbonization in energy-intensive industries, such as steel, glass, and aluminum, contributing around 30% of global greenhouse gas emissions (IEA, 2023). The glass industry alone generated 18 Mt of CO_2 emissions in Europe in 2020 (EEA, 2020), underscoring the need for effective decarbonization strategies. These elevated emissions primarily result from the industry's reliance on high-temperature processes, such as the glass melting process. As technological advancements to improve energy efficiency have matured, switching to a clean fuel like hydrogen for the combustion process has emerged as the most impactful strategy for decarbonization (Collina et al., 2023). Given the sector's reliance on long-term strategic investments, today's decisions are critical to achieving future decarbonization goals (Zier et al., 2023). Therefore, addressing the challenges associated with hydrogen adoption has become an urgent priority, with the H2GLASS initiative actively working to demonstrate its feasibility (H2GLASS, 2023).

One challenge in transitioning to hydrogen is ensuring a continuous and sufficient fuel flow to meet energy requirements. This is essential for maintaining stable combustion conditions and preventing adverse impacts on heating efficiency and glass quality (Fachini et al., 2017). The current reliance on natural gas and the lack of hydrogen infrastructure in manufacturing plants present a significant barrier to hydrogen adoption (Diesing et al., 2025). This underscores the need for a tool to help glass manufacturers estimate the hydrogen flow and infrastructure capacity required for this transition.

Moreover, hydrogen's lower volumetric energy content than natural gas poses economic feasibility concerns, particularly for hydrogen produced through low-carbon methods (Del Rio et al., 2022). This highlights the importance of assessing the economic implications of such a shift.

Another major challenge is the environmental impact. Hydrogen combustion itself produces no direct CO_2 emissions, but transitioning to hydrogen can still result in significant indirect CO_2 emissions, depending on the production method. Green hydrogen, produced via water electrolysis powered by renewable energy sources, is the most sustainable option. The effectiveness of yellow hydrogen, produced via water electrolysis using electricity from the grid, is highly dependent on the specific context. Grey hydrogen, the most affordable and commercially available option, is associated with high indirect CO_2 emissions due to its fossil fuels-based production (Ustolin et al., 2022). This emphasizes the need for a thorough assessment of hydrogen's environmental impact.

To help overcome these challenges, this paper presents a mathematical model to evaluate the economic and environmental impacts of hydrogen adoption in glass manufacturing. Building on existing models in the literature, the proposed model also estimates the required hydrogen flow and infrastructure capacity, providing valuable insights to support glass manufacturers in making informed investment decisions. The model only uses aggregated data, making it straightforward to apply, and can be extended to incorporate other considerations, such as safety. The model is applied to a case study, and a scenario analysis is conducted by varying the electricity source and the type of hydrogen externally supplied.

The structure of this paper is as follows: Section 2 reviews relevant literature and highlights this study's contributions. Section 3 describes the system and case study under investigation. Section 4 outlines the mathematical model for system components' behavior, as well as related costs and CO_2 emissions. Section 5 presents and discusses the results, and Section 6 concludes with key findings, limitations, and future research directions.

10.1016/j.ifacol.2025.09.032

2. RELEVANT LITERATURE

While hydrogen is a promising solution for decarbonizing the glass industry (Zier et al., 2021; Del Rio et al., 2022), related quantitative studies remain limited, addressing diverse aspects and employing different methodologies.

For instance, Gärtner et al. (2021) analyzed the economic and environmental impacts of hydrogen use in oxyfuel glass melting, simulating hydrogen production via water electrolysis powered by solar and wind. Through Life Cycle Assessment, Wulf and Zapp (2022) evaluated the environmental impact of different alternatives for introducing hydrogen in the glass sector. Zier et al. (2023) employed a bottom-up modeling approach with the same objective. Meanwhile, Collina et al. (2024) analyzed the hydrogen introduction in glass manufacturing with a safety perspective, highlighting the benefits of applying a risk-based maintenance approach. Lastly, Fragapane et al. (2024) performed a cost analysis of hydrogen implementation in glass manufacturing.

Beyond the glass sector, several studies have assessed the economic and environmental impacts of hydrogen integration. The common approach involves modeling hourly operations over a year, serving as a reference for the system's lifetime.

Among these studies, Marocco et al. (2023) evaluated the introduction of hydrogen as fuel in the steel industry, produced through grid-powered electrolysis. Superchi et al. (2023) investigated using hydrogen, produced through wind-powered electrolysis, as a reducing agent in steelmaking. Trapani et al. (2023) focus on the semiconductor industry, considering hydrogen produced by leveraging solar and including an external hydrogen supply modeled as continuous. Sousa et al. (2024) explored hydrogen production via solar and wind sources to decarbonize the ceramics sector.

All the works cited above use highly granular data, which is often a combination of real and simulated data due to the limited availability of real data. They also need long computational times due to the large number of (hourly) variables involved. However, hydrogen integration and investment in hydrogen-related infrastructure are strategic decisions (Ackoff, 2020). In most practical applications, aggregated data offers sufficient insights for reliable long-term decisions and is usually more readily available.

This paper offers a strategic planning model that only uses aggregated data and is, as a result, easy to implement and modify. This aggregate approach also enables novel model enhancements not present in the existing literature, such as a queueing approach for truck delivery frequency.

Additionally, to the best of our knowledge, hydroelectric power has not been considered in quantitative studies of hydrogen adoption despite being the most used renewable for electricity generation in Europe (IEA, 2022). Providing a steady power source (Cooper et al., 2022), it is particularly well-suited for application in the glass sector, where the continuous hydrogen supply is critical. Hence, the proposed model considers hydropower as an alternative energy source.

3. SYSTEM DESCRIPTION

Figure 1 shows a schematic representation of the system investigated, primarily based on the conceptual design developed for an experimental setup within the H2GLASS project (H2GLASS, 2023).

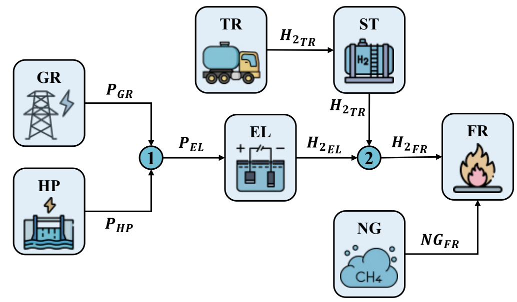

Figure 1. Schematic representation of the system

Experts' input has been essential to validate the main components, their functions, and the flows within the system. The system includes an electrolyzer (EL), powered either by the electrical grid (GR) or hydropower (HP), trucks delivering hydrogen (TR), a hydrogen storage tank (ST), and a glass melting furnace where the combustion process occurs (FR), currently using only natural gas (NG). The case study focuses on a glass company in France that currently meets its electricity needs with green energy from a nearby hydroelectric dam. The access to hydropower has been an additional key driver in selecting this source as the primary renewable explored in this study. As an alternative, the French electrical grid is a relatively low-carbon option, comprising nuclear energy (64%), hydropower (12%), wind (10%), and natural gas (6%) (IEA, 2023). Since the glass sector is part of the European Emission Trading System (EU ETS), penalties for direct emissions are included in the model. No additional carbon taxes are considered, as companies covered by the EU ETS are generally exempt from France carbon tax.

4. MATHEMATICAL MODEL

4.1 Notation

Table 1 provides an overview of the model notation, detailing decision variables, parameters (including the values used, rounded to two decimal places), and outputs.

Table 1. Model notation

Not.	Description	Unit	Value
Decision Variables			
P_{EL}	Rated power EL	MW	-
$\%H_2$	Minimum H_2 percentage	-	-
λ	Arrival rate TR	truck/h	-
V_{ST}	Volume ST	m^3	-
Parameters			
NG_D	Avg. hourly NG demand	Nm^3/h	Conf.
LHV_{NG}	Lower heating value NG	kWh/Nm^3	10.17
LHV_{H_2}	Lower heating value H_2	kWh/Nm^3	2.99
T	Hours in a year	h/year	8760
η_{EL}	Nominal efficiency EL	-	0.55
C_{TR}	H_2 capacity TR	Nm^3/truck	4000
u	Unloading time TR	h	1
n_D	Maximum receiving docks	-	5
LBC_{ST}	Minimum filling % ST	-	0.20
P_A	Atmospheric pressure	bar	1
P_{ST}	Target pressure ST	bar	50
c_{NG}	Cost NG	€/Nm^3	0.52
c_{CO_2}	CO_2 allowance price	€/kg	0.08

c_{GR}	Electricity cost GR	€/kWh	0.13
c_{HP}	Electricity cost HP	€/kWh	0.06
c_1	Cost coefficient 1 EL	$/kW	1047
c_2	Cost coefficient 2 EL	$/kW	-3.48
c_3	Cost coefficient 3 EL	$/kW	2062
c_4	Cost coefficient 4 EL	$/kW	-0.26
ϵ	Exchange rate	€/$	0.90
c_w	Water consumption cost	€/Nm^3	0.01
c_{sr}	Stack replacement % cost	-	0.40
l_s	Stack lifetime	year	10
$c_{O\&M}$	O&M % cost	-	0.02
c_L	Labor cost TR unloading	€/truck*h	42
c_{H_2}	Cost H_2 delivered (grey)	€/Nm^3	0.18
	Cost H_2 delivered (green)	€/Nm^3	0.72
c_{TR}	Investment cost TR	k€/truck	100
c_{ST}	Unitary investment cost ST	€/m^3	2245
MM_{CO_2}	Molar mass CO_2	g/mol	44.01
MM_{CH_4}	Molar mass methane (CH_4)	g/mol	16.04
ρ_{CH_4}	Density CH_4	kg/Nm^3	0.72
ρ_{H_2}	Density H_2	kg/Nm^3	0.09
ε_{GR}	Emission factor GR	kg/kWh	0.06
ε_{HP}	Emission factor HP	kg/kWh	0.02
ε_{H_2}	Emission factor H_2 (grey)	kg/Nm^3	0.85
	Emission factor H_2 (green)	kg/Nm^3	0.10
ε_{TR}	Emission factor TR	g/kmNm^3	0.19
D_{TR}	Delivery distance TR	km	220
d	Discount rate	/year	0.04
N	System lifetime	year	20
Outputs			
H_{2FR}	Avg. hourly H_2 consumed	Nm^3/h	-
NG_{FR}	Avg. hourly NG consumed	Nm^3/h	-
H_{2EL}	Avg. hourly H_2 produced	Nm^3/h	-
H_{2TR}	Avg. hourly H_2 delivered	Nm^3/h	-
P_{GR}	GR electricity consumed	MWh	-
P_{HP}	HP electricity consumed	MWh	-
B	Maximum TR unloading	truck	-
C_{ST}	Required capacity ST	Nm^3	-
IC_{EL}	Investment cost EL	€	-
IC_{TR}	Investment cost TR	€	-
IC_{ST}	Investment cost ST	€	-
OC_{NG}	Annual cost NG	€/year	-
OC_P	Annual cost electricity	€/year	-
OC_{EL}	Annual cost EL	€/year	-
OC_{TR}	Annual cost TR	€/year	-
CO_2	Annual CO_2 emissions	kg/year	-
CO_{2P}	Annual CO_2 electricity	kg/year	-
CO_{2TR}	Annual CO_2 TR	kg/year	-
CO_{2NG}	Annual CO_2 NG	kg/year	-
$\% CO_{2V}$	CO_2 % variation	-	-

4.2 System components modeling

Equations (1) and (2) demonstrate the system's flow balance.

$$P_{EL} = P_{GR} + P_{HP} \tag{1}$$

$$H_{2FR} = H_{2EL} + H_{2TR} \tag{2}$$

Given the current average consumption of natural gas and the minimum required percentage of hydrogen in the fuel mix, (3) establishes the required hydrogen supply to the furnace, which considers the different lower heating values (LHV) of the fuels. Consequently, (4) estimates the amount of natural gas still required for the combustion process.

$$H_{2FR} \geq \%H_2 * NG_D * \frac{LHV_{NG}}{LHV_{H_2}} \tag{3}$$

$$NG_{FR} = NG_D - \left(H_{2FR} * \frac{LHV_{H_2}}{LHV_{NG}}\right) \tag{4}$$

Hydrogen can be produced on-site through a Proton Exchange Membrane (PEM) electrolyzer. Equation (5) calculates the average hourly hydrogen production assuming nominal capacity and efficiency.

$$H_{2EL} = \frac{P_{EL} * 1000 * \eta_{EL}}{LHV_{H_2}} \tag{5}$$

Additionally, compressed hydrogen can be supplied externally via trucks. Based on a specified truck arrival rate, calculated as an integer number of trucks per week, (6) represents the average hourly hydrogen delivered.

$$H_{2TR} = \lambda * C_{TR} \tag{6}$$

To ensure that the number of trucks unloading hydrogen simultaneously does not exceed the facility's maximum receiving docks (with 99% probability), constraints (7) and (8) are imposed on the arrival rate, derived directly from the Poisson distribution:

$$1 - \left(\sum_{b=0}^{B} \frac{(\lambda u)^b * e^{-\lambda u}}{b!}\right) \leq 0.01 \tag{7}$$

$$B \leq n_D \tag{8}$$

When relying on the external supply, a storage tank must accommodate the hydrogen exceeding the furnace's immediate requirements. Equation (9) estimates the tank capacity, which is sized to cover the difference between the maximum unloading rate (based on the highest number of trucks unloading) and the maximum hydrogen demand rate (when the electrolyzer is inactive). A minimum filling percentage is considered.

$$C_{ST} = \frac{\left(B * \frac{C_{TR}}{u} - H_{2FR}\right) * u}{(1 - LBC_{ST})} \tag{9}$$

Based on the target storage pressure, constraint (10) is applied to determine the required tank volume, considered an integer value, to meet the necessary storage capacity.

$$V_{ST} \geq \frac{C_{ST} * P_A}{P_{ST}} \tag{10}$$

4.3 CO_2 emissions modeling

As hydrogen is introduced into the glass manufacturing process to reduce CO_2 emissions, evaluating the environmental impact of various design solutions is essential. Equations (11) – (14) estimate the CO_2 emissions associated with natural gas combustion, electricity consumption, and truck deliveries (including indirect emissions from transportation and hydrogen production methods).

$$CO_2 = CO_{2_{NG}} + CO_{2_P} + CO_{2_{TR}} \tag{11}$$

$$CO_{2_{NG}} = NG_{FR} * \frac{MM_{CO_2}}{MM_{CH_4}} * \rho_{CH_4} * T \tag{12}$$

$$CO_{2_P} = (\varepsilon_{GR} * P_{GR} + \varepsilon_{HP} * P_{HP}) * 1000 * T \tag{13}$$

$$CO_{2_{TR}} = \left(\varepsilon_{H_2} * H_{2_{TR}} + \frac{\varepsilon_{TR}}{1000} * \lambda * C_{TR} * D_{TR}\right) * T \tag{14}$$

The reduction in CO_2 emissions is assessed against the current scenario, where only natural gas is used for combustion. In this baseline scenario, (11) includes only $CO_{2_{NG}}$, as both CO_{2_P} and $CO_{2_{TR}}$ are zero, reflecting that the current scenario neither requires electricity to power an electrolyzer nor involves external hydrogen deliveries. Additionally, in (12), NG_{FR} coincides with the current average hourly natural gas demand NG_D, as no hydrogen is utilized.

4.4 Components cost modeling

Equation (15) estimates the annual operating cost of natural gas, which includes CO_2 allowance prices.

$$OC_{NG} = NG_{FR} * c_{NG} * T + CO_{2_{NG}} * c_{CO_2} \tag{15}$$

Both investment and operating costs must be estimated for the electrolyzer. The investment cost is assumed to depend on its rated power, following the exponential function shown in (16), which has been adopted by Astriani et al. (2024).

$$IC_{EL} = P_{EL} * 1000 * \epsilon * (c_1 + c_2 * P_{EL} + c_3 * e^{c_4 * P_{EL}}) \tag{16}$$

Equation (18) estimates the electrolyzer's operating cost, including electricity costs, further detailed in (17), water consumption costs, stack replacement expenses and operation and maintenance (O&M) costs.

$$OC_P = (c_{GR} * P_{GR} + c_{HP} * P_{HP}) * 1000 * T \tag{17}$$

$$OC_{EL} = OC_P + H_{2_{EL}} * c_w * T + \left(\frac{c_{sr}}{l_s} + c_{O\&M}\right) * IC_{EL} \tag{18}$$

Similarly, investment and operating costs are considered for external hydrogen supply and calculated using (19) and (20). The investment cost covers the infrastructure required to receive hydrogen (piping, high-pressure hose, pressure reduction station, safety equipment, etc.) and depends on the number of trucks that need to be accommodated for simultaneous unloading. The operating costs for external hydrogen supply include the cost of delivered hydrogen (depending on its type), labor costs for unloading activities, and a fixed percentage for O&M.

$$IC_{TR} = B * c_{TR} \tag{19}$$

$$OC_{TR} = \left(c_{H_2} * H_{2_{TR}} + c_L * \lambda * u\right) * T + c_{O\&M} * IC_{TR} \tag{20}$$

The same cost components are evaluated for the storage tank and represented by (21) and (22). The investment cost is assumed to be a linear function of the storage requirements (Marocco et al., 2023), while the annual operating cost of the storage tank is estimated through a fixed percentage for O&M.

$$IC_{ST} = c_{ST} * V_{ST} \tag{21}$$

$$OC_{ST} = c_{O\&M} * IC_{ST} \tag{22}$$

4.5 Objective function

Equation (23) shows the objective function, represented by the net present cost (NPC) of the system and expressed in €.

$$NPC = \sum_{i=EL,TR,ST} IC_i + \sum_{n=1}^{N} \frac{\sum_{j=NG,EL,TR,ST} OC_j}{(1+d)^n} \tag{23}$$

The first term represents the investment costs for hydrogen-related components, while the second accounts for the net present operating costs for all components over the system lifetime, discounted to present value using a discount rate.

4.6 Economic and environmental indicators

Equations (24) and (25) present the economic indicators incorporated into the model (Marocco et al., 2023; Trapani et al., 2023; Sousa et al., 2024).

The levelized cost of hydrogen (LCOH), expressed in €/kg, is a particularly valuable metric for validating the model and comparing different hydrogen supply scenarios. The levelized cost of energy (LCOE), expressed in €/kWh, is useful for practitioners in evaluating economic feasibility.

$$LCOH = \frac{IC_{EL} + IC_{TR} + IC_{ST} + \sum_{n=1}^{N} \frac{\sum_{j=EL,TR,ST} OC_j}{(1+d)^n}}{\sum_{n=1}^{N} \frac{H_{2_{FR}} * \rho_{H_2} * T}{(1+d)^n}} \tag{24}$$

$$LCOE = \frac{NPC}{\sum_{n=1}^{N} \frac{(H_{2_{FR}} * LHV_{H_2} + NG_{FR} * LHV_{NG}) * T}{(1+d)^n}} \tag{25}$$

Lastly, the percentage variation in CO_2 emissions against current operations, denoted as $\%CO_{2_V}$, is included to measure the environmental impact of the supply solution.

5. RESULTS AND DISCUSSION

The analysis was conducted across multiple scenarios, considering different electricity sources, selected based on the case study context, and types of hydrogen externally supplied. The authors conventionally selected two common hydrogen types, as they exhibit significant differences in economic and environmental implications.

Notably, across all scenarios, when no constraints on hydrogen usage are imposed, the solution with the lowest NPC is to continue to rely exclusively on natural gas as a fuel, resulting in an NPC of approximately 16,753 k€ and an LCOE of 0.07 €/kWh. This option requires no investment in hydrogen-related infrastructure, but it fails to meet decarbonization targets. To address this, different minimum required percentages of hydrogen in the fuel mix are considered for the rest of the analysis. Figure 2 summarizes the results.

The first scenario analyzed, Scenario A, assumes reliance on the grid to meet the additional electricity demand due to the electrolyzer and truck delivery of grey hydrogen (the most common type available). In this scenario, the most economically viable hydrogen supply solution, offering the lowest LCOH, relies entirely on external hydrogen delivery

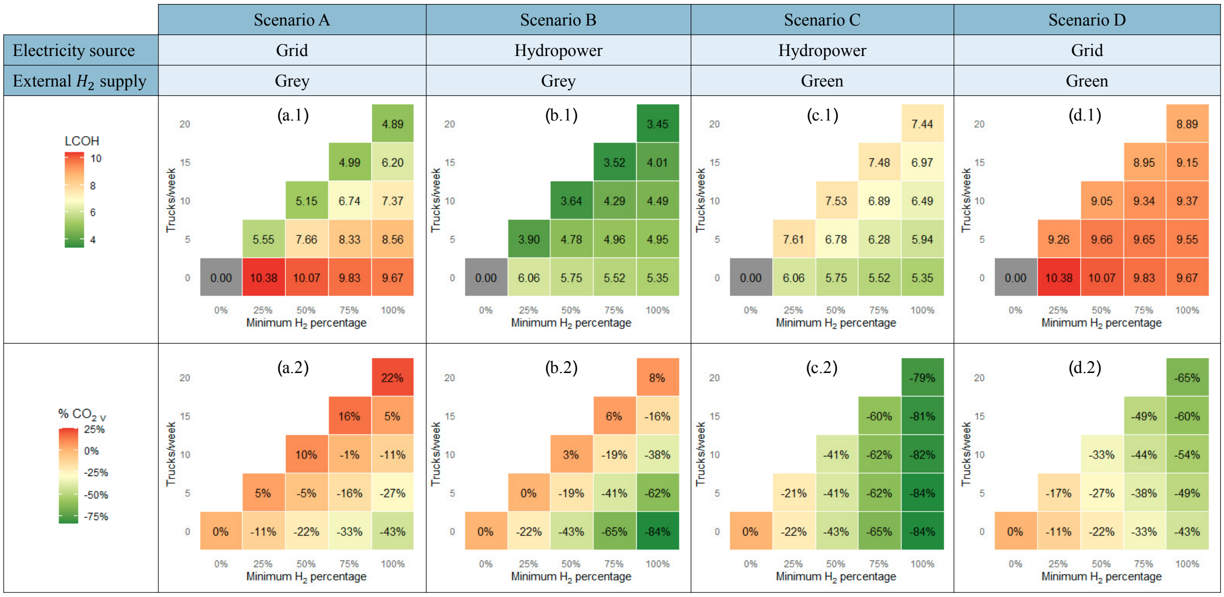

Figure 2. Impact of minimum required H_2 percentage in the fuel mix and external supply on LCOH and $\%CO_{2_V}$ for different scenarios

(Figure 2a.1). However, these solutions result in CO_2 emissions exceeding current levels (Figure 2a.2). This is due to hydrogen's significantly lower heating value, requiring approximately three times the volume of hydrogen compared to natural gas to deliver the same energy, offsetting its lower emissions per unit of fuel. On the other hand, a maximum achievable CO_2 emissions reduction of 43% can be obtained by fully switching to hydrogen as fuel and producing it entirely on-site. However, this approach is not economically favorable, given its associated LCOE of 0.29 €/kWh, over four times the current fuel cost. Consequently, Scenario A is unsuitable from either an economic or environmental perspective. Producing hydrogen using lower emission methods is essential to serve as a more effective solution in glass manufacturing decarbonization. Addressing the additional electricity demand by utilizing hydropower would yield better results. In this scenario, referred to as Scenario B, the most economical solution remains to rely on external supply (Figure 2b.1). However, fully producing hydrogen on-site using hydropower sees a decrease in LCOH from 9.67 €/kg to 5.35 €/kg compared to the grid (Figures 2a.1 and 2b.1). This approach is also linked to significant CO_2 percentage reduction (Figure 2b.2), achieving a maximum reduction of 84% when all hydrogen is produced on-site. However, the fuel cost remains substantially higher than in the current natural gas-based scenario. For complete hydrogen adoption and on-site production, which is associated with the highest decarbonization outcome, the LCOE can reach up to 0.16 €/kWh. This is more than twice as high as the current scenario but significantly lower than the respective case in Scenario A. Considering the growing number of electrolysis projects (IEA, 2024), scenarios where green hydrogen can be outsourced are also evaluated. Scenario C continues to assume the use of hydropower to power the electrolyzer paired with sourcing green hydrogen by truck. In this scenario, the preferred solution from an economic perspective, particularly at higher hydrogen percentages, shifts to on-site production (Figure 2c.1). This shift is driven by the decreasing cost of hydrogen production, attributed to economies of scale in the electrolyzer capacity investments and the relatively low cost of hydropower compared to other renewable energy sources used for green hydrogen production. In this scenario, outsourcing part of hydrogen production has no significant impact on CO_2 emissions, apart from a small share likely associated with transportation (Figure 2c.2). The associated LCOE for a complete transition with on-site production remains the same as in Scenario B (0.16 €/kWh), as only hydrogen is utilized, and the entire electricity demand is met through hydropower.

The final scenario, Scenario D, extends the analysis to cases where hydropower is unavailable, necessitating the electrolyzer to be powered by the electrical grid. Under these conditions, hydrogen supply generally becomes the most expensive option, though outsourcing production achieves a slightly lower LCOH (Figure 2d.1). Moreover, outsourcing results in higher CO_2 reduction percentages (Figure 2d.2). LCOE for the reference case is the same as in Scenario A (0.29 €/kWh) due to the same electricity source.

6. CONCLUSIONS

This paper presented a model for hydrogen supply in the glass manufacturing sector, considering both economic and environmental considerations. In all analyzed scenarios, the most economical solution remains to rely on natural gas, which fails to meet decarbonization requirements. When hydropower availability is restricted to current demand levels, the introduction of hydrogen either does not yield significant improvements or is not economically favorable. Achieving substantial decarbonization of the glass sector (up to 84% reduction in CO_2 emissions) requires the electrolyzer to be powered by green electricity. Due to the economic benefits of hydropower over other renewable sources and the economies of scale associated with electrolyzer capacity, relying on external green hydrogen supply becomes less favorable. Nonetheless, incentivizing the adoption of hydrogen remains crucial to encourage its integration into the sector. The model presented serves as a practical tool for glass manufacturers to preliminary assess the financial and environmental impacts of incorporating hydrogen into their production processes, including the necessary infrastructure investments. While relying on aggregated data may result in less detailed analysis and potentially suboptimal solutions, it allows easy application and understanding, including the possibility of quickly testing many scenarios. Additionally, the modeling approach is well-suited for easily integrating safety evaluations, which are critical given the hazardous properties of hydrogen (Collina et al., 2023). Ensuring a reliable hydrogen supply by mitigating the risks of adverse events is essential for safe and sustainable operations. Future studies will focus on integrating safety considerations into the design of hydrogen supply systems and extending the model to other renewable energy sources.

ACKNOWLEDGEMENTS

This work received funding 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

Collina, G., Wan, P.K., Paltrinieri, N., and Bucelli, M. (2023). Risk-Based Maintenance models for hydrogen systems: A review for the glass and aluminium industry. *Institution of Chemical Engineers Symposium Series*, 170. Scopus.

Collina, G., Cantini, A., Leoni, L., Ferraro, S., De Carlo, F., Bucelli, M., and Paltrinieri, N. (2024). Hydrogen in Glass Sector: A Comparison between Risk-Based Maintenance and Time-Based Maintenance Approaches. *IFAC-PapersOnLine*, *58*(8), 109–114. https://doi.org/10.1016/j.ifacol.2024.08.058

Cooper, N., Horend, C., Röben, F., Bardow, A., Shah, N. A Framework for the Design & Operation of a Large-Scale Wind-Powered Hydrogen Electrolyzer Hub. *International Journal of Hydrogen Energy*, 47 (14), 8671–86. https://doi.org/10.1016/j.ijhydene.2021.12.225.

Diesing, P., Lopez, G., Blechinger, P., Breyer, C. (2025). From Knowledge Gaps to Technological Maturity: A Comparative Review of Pathways to Deep Emission Reduction for Energy-Intensive Industries. *Renewable and Sustainable Energy Reviews*, 208, 115023. https://doi.org/10.1016/j.rser.2024.115023.

EEA. (2020). European Union Emissions Trading System. https://www.eea.europa.eu/en/datahub/datahubitemview/98f04097-26de-4fca-86c4-63834818c0c0.

Fachini, R.F., Esposto, K.F., Camargo, V.C.B. (2017). Glass Container Production Planning with Warm-Ups and Furnace Extraction Variation Losses. *The International Journal of Advanced Manufacturing Technology*, 90 (1–4), 527–43. https://doi.org/10.1007/s00170-016-9369-7.

Fragapane, G., Wan, P.K., Ortiz, M.M., and Silva, T.L. (2024). Impact of Hydrogen Integration and Implementation on Costs in Glass Production. *Procedia CIRP*, 130, 1776–83. https://doi.org/10.1016/j.procir.2024.10.315.

Furszyfer Del Rio, D.D., Sovacool, B.K., Foley, A.M., Griffiths, S., Bazilian, M., Kim, J., Rooney, D. (2022). Decarbonizing the Glass Industry: A Critical and Systematic Review of Developments, Sociotechnical Systems and Policy Options. *Renewable and Sustainable Energy Reviews*, 155, 111885. https://doi.org/10.1016/j.rser.2021.111885.

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), 8603. https://doi.org/10.3390/en14248603.

H2GLASS. (2023). H2GLASS - Decarbonise our future. H2GLASS. https://h2-glass.eu/

International Energy Agency. IEA Report, Industry–CO2 Emissions. https://www.iea.org/energy-system/ industry

International Energy Agency. IEA. Energy system of France. https://www.iea.org/countries/france/electricity

International Energy Agency. IEA Report, Global Hydrogen Review 2024. https://www.iea.org/reports/global-hydrogen-review-2024.

Marocco, P., Gandiglio, M., Audisio, D., Santarelli, M. (2023). Assessment of the Role of Hydrogen to Produce High-Temperature Heat in the Steel Industry. *Journal of Cleaner Production*, 388, 135969. https://doi.org/10.1016/j.jclepro.2023.135969.

Sousa, J., Azevedo, I., Camus, C., Mendes, L., Viveiros, C., Barata, F. (2024). Decarbonizing Hard-to-Abate Sectors with Renewable Hydrogen: A Real Case Application to the Ceramics Industry. *Energies*, 17 (15), 3661. https://doi.org/10.3390/en17153661.

Superchi, F., Mati, A., Carcasci, C., Bianchini, A. (2023). Techno-Economic Analysis of Wind-Powered Green Hydrogen Production to Facilitate the Decarbonization of Hard-to-Abate Sectors: A Case Study on Steelmaking. *Applied Energy*, 342, 121198. https://doi.org/10.1016/j.apenergy.2023.121198.

Trapani, D., Marocco, P., Gandiglio, M., Santarelli, M. (2023). Optimal Design of Renewable Power-To-Hydrogen Systems for the Decarbonization of a Semiconductor Industry. *36th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2023)*, 2523–31. https://doi.org/10.52202/069564-0227.

Ustolin, F., Campari, A., Taccani, R. (2022). An Extensive Review of Liquid Hydrogen in Transportation with Focus on the Maritime Sector. *Journal of Marine Science and Engineering*, 10 (9), 1222. https://doi.org/10.3390/jmse10091222.

Wulf, C., Zapp, P. (2022). Analyzing the Future Potential of Defossilizing Industrial Specialty Glass Production with Hydrogen by LCA. *Procedia CIRP*, 105, 666–71. https://doi.org/10.1016/j.procir.2022.02.111.

Zier, M., Stenzel, P., Kotzur, L., Stolten, D. (2021). A Review of Decarbonization Options for the Glass Industry. *Energy Conversion and Management: X*, 10, 100083. https://doi.org/10.1016/j.ecmx.2021.100083.

Zier, M., Pflugradt, N., Stenzel, P., Kotzur, L., Stolten, D. (2023). Industrial Decarbonization Pathways: The Example of the German Glass Industry. *Energy Conversion and Management: X*, 17, 100336. https://doi.org/10.1016/j.ecmx.2022.100336.