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Impact of Hydrogen Integration and Implementation on Costs in Glass Production

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Abstract

The glass industry stands as a significant contributor to global greenhouse gas emissions, primarily reliant on natural gas during production, posing a considerable environmental challenge. Despite advancements in furnace technologies, achieving substantial reductions in emissions remains a hurdle. Radical redesigns, including advanced heat recovery systems and alternative fuel sources such as hydrogen, emerge as promising avenues. However, current projections indicate modest increases in energy efficiency, insufficient to align with decarbonization objectives. Hydrogen appears promising, offering drastic emissions reductions and operational flexibility. The European glass industry is increasingly considering hydrogen as a sustainable alternative. However, the transition necessitates a comprehensive understanding of the economic implications associated with different delivery and implementation methods. This study developed a simulation model based on empirical data from a case study and analyzed different scenarios with the aim of providing insights into the cost implications of various hydrogen delivery and implementation methods for glass production. The study contributes to providing decision support methodologies and empowering production planners and managers in the glass industry to make informed decisions toward sustainable and economically viable decarbonization strategies.

Keywords: Hydrogen; Glass production, Decarbonization; Cost model.

1. Introduction

The glass industry stands as a significant contributor to global greenhouse gas emissions, primarily reliant on natural gas during production, thus posing a considerable environmental challenge. Despite advancements in furnace technologies aimed at enhancing efficiency, the industry continues to face hurdles in achieving substantial reductions in emissions. As the world strives to meet ambitious climate targets, it becomes imperative for the glass sector to embark on a journey towards decarbonization.

In recent years, efforts to improve efficiency in glass production have encountered the "plateau of diminishing returns," where further enhancements yield minimal reductions in emissions, and emissions have remained quite stable at approximately 18 Mt CO_2 eq [1]. Radical redesigns, including the integration of advanced heat recovery systems, digital technologies, or alternative fuel sources such as hydrogen, emerge as promising avenues for achieving significant improvement progress. However, furnace modification, digital technologies, or innovations in heat recovery systems, current projections suggest a modest 10-15% increase in energy efficiency, insufficient to align with the stringent decarbonization objectives outlined in initiatives like the Fit For 55 Plan and the net-zero greenhouse gas emissions target for 2050 [2], [3]. Among the proposed solutions, transitioning from fossil fuels to renewable electricity or hydrogen fuel appears most promising. Electric melting furnaces offer advantages such as minimal direct emissions and improved energy efficiency, yet they face

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limitations in scalability and operational flexibility [4]. In contrast, hydrogen presents a compelling alternative, with the potential to drastically reduce CO_2 emissions, enhance energy efficiency, and maintain furnace longevity. Additionally, hydrogen's versatility allows for seamless integration into existing furnace setups, offering a practical solution for industry-wide adoption.

With significant advancements in electrolyzer technology, more economical hydrogen production is becoming feasible in the long run and has piqued the interest of other energy-intensive industries to shift towards greener production [5], [6]. PEM electrolysis and alkaline electrolysis are both methods of water electrolysis used to produce hydrogen.

Amidst growing geopolitical complexities affecting natural gas procurement, the European glass industry is increasingly turning to hydrogen as a sustainable alternative. However, the transition necessitates a comprehensive understanding of the economic implications associated with different delivery and implementation methods. To our knowledge, existing literature lacks a thorough cost analysis including H2 and to guide decision-making processes within the glass production sector.

In response to this gap, this research endeavors to develop a simulation model based on empirical data from a case study, aiming to analyze and provide insights into the cost implications of various hydrogen delivery and implementation methods for glass production. By offering decision support methodologies, this study seeks to empower glass producers in making informed choices toward sustainable and economically viable decarbonization strategies.

2. Theoretical background

Several cost model approaches and methods for glass production have been introduced in recent years. Gopisetti (2008) introduces a cost model that delineates material costs, energy costs, depreciation costs, and overhead expenses, including warehouse costs, indirect materials cost, labor costs, and selling expenses for a specified order quantity within the glass industry. The study supports managers in decision-making for production variables and associated costs of glass products [7]. Abuizam (2012) demonstrates in a case study how spreadsheet modeling can effectively address linear programming problems without algebraic formulations [8]. The model is based on the Juleno Crystals use case, maximizing the company's profit while accurately integrating fixed costs and adhering to available resource constraints. Furthermore, many studies have defined pathways, delivery methods, and implementation methods for H2 in glass production and have defined system boundaries of such calculations based on techno-economic or Life Cycle Assessment (LCA) assessments, providing baselines to build a cost model for glass production with H2. Demir et al. (2018) conduct a comparative performance and cost assessment of three different hydrogen delivery pathways encompassing storage, transmission, and distribution stages. Various methods for hydrogen transportation, including pressurized tanks, cryogenic liquid tankers, and gas pipelines, are scrutinized alongside transmission options from distribution centers to consumers [9]. The analysis encompasses calculations of hydrogen production capacity, levelized cost of energy distribution ($/kg), infrastructure costs, environmental impact (GHG emissions), and application parameters. The highest levelized cost of delivery stands at $8.02/kg H2 for the first scenario, whereas the lowest is $2.73/kg H2 for the third scenario. Moreover, Sgarbossa et al., (2023) initially introduce a planning matrix for Renewable Hydrogen Supply Chains (HSCs), via a content analysis-based literature review. Subsequently, they propose a research agenda aimed at facilitating optimal solutions for planning tasks, with a focus on emerging topics and areas in renewable HSC studies [10]. This agenda aligns with hydrogen strategies and roadmaps, considering various phases of adoption and market development. A comprehensive overview of potential challenges and methodologies for operations, supply chain managers, and researchers to tackle in the future is provided. Gärtner et al., (2021) develop a simulation and conduct Techno-Economic Analysis of a Power-to-Hydrogen Process for Oxyfuel Glass Melting [11]. The study presents a process concept for the step-wise integration of PtH2 processes into oxyfuel glass melting based on simulations. This approach enables the evaluation of changes in specific energy demand and associated specific CO_2 emissions concerning the H2 content in the fuel mixture, fuel composition, combustion, and certain furnace parameters. Wulf et al., (2022) conduct a case research assessment utilizing the national grid mix of Germany to power the electrolyzers [12]. System boundaries are defined, providing a solid baseline for the cost model. The comparison is furthered by the production of off-site hydrogen transported to the glass trough, either as conventional liquefied hydrogen in cooling tanks by truck or in hydrogen pipelines.

Moreover, important economic evaluation parameters include the production of hydrogen with electrolyzers. Terlouw et al., (2022) demonstrate that the production cost of H2 via electrolysis can decrease to approximately €4 today and further down to €2 per kg H2 by 2040 [13]. They emphasize the importance of a specific location with high availability, stable energy sources (e.g., electricity grid combined with wind power), and sufficient land size for cost-effectiveness . Material efficiency of PEM electrolyzers is vital to avoid potentially excessive costs for scarce materials. Yang et al., (2023) underscore that the lifetime of the electrolyzer significantly impacts the cost of hydrogen production, predicting that the cost using ALK electrolyzers will be 24% and 51% lower than AEM and PEM electrolyzers, respectively, in the short term (less than 2 years). In the medium and long term, AEM and PEM are expected to be 24% and 56% lower, respectively [14]. Additionally, besides construction and labor costs, it's imperative to consider various possible tax deductions such as carbon dioxide emissions when utilizing electrolyzers [15]. This research aims to bridge the gap by providing an economic analysis of costs for glass production fueled with H2 and different delivery methods.

3. Method

This study employed a mixed-methods approach, integrating both qualitative and quantitative methodologies to enhance the credibility and applicability of the findings. The research methodology comprises simulation modeling and a detailed case study aimed at fulfilling the study's objectives.

The simulation aspect, focusing on analyzing the impact of H2 utilization in glass production, will be executed using an optimization model named HyOpt [16]. HyOpt, a widely utilized tool in numerous research endeavors, offers optimization capabilities for investment, capacity enhancement, and the operation of hydrogen-based energy systems. While the original model is formulated in FICO®'s Mosel Language, the current analysis employs an implementation in Julia, ensuring compatibility and efficiency.

Concurrently, the case study was conducted at a prominent European glass manufacturing facility specializing in container glass production, which is transitioning its operations towards hydrogen-based production. The simulation modeling is tailored to the specifics of this case, with variable ranges elaborated in Section 3.2 and various scenarios explored, as detailed in Section 3.3.

3.1 Simulation Modelling

This model is based on nodes and edges that represent the relevant technologies, energy carriers, and other products of the energy system. Regarding the time structure, HyOpt utilizes a two-level time definition: at a higher level, strategic periods determine when the model is allowed to make investments and increase the capacity of a given technology. For each strategic period, operational periods are defined. These operational periods cover representative operations (which could be a year, several weeks, days, etc.) that allow capturing the effect of the system's operation on the total costs.

Regarding nodes, they are defined based on their function, distinguishing between Market and Plant nodes in the presented analysis. Market nodes represent the supply of raw materials and energy carriers, such as natural gas and electricity from the grid, along with the purchase costs associated with them. A Market node is also used to represent bottle demand, accounting for the income of the analyzed system. Plant nodes are entities that transform products or energy carriers, such as the glass furnace, the production line, or the electrolysis plant.

Regarding the objective function considered by the model, it maximizes the total Net Present Value (NPV) of the system, considering costs associated with investment in new capacity, operation of the system, as well as the income provided by selling the bottles to the market. Additions to the framework on the gas production value chain entail segmenting the typical glass production value chain into some source nodes (grid, raw materials, natural gas market), a furnace, the production lines, and a glass market node. The market nodes are already formulated in HyOpt, whereas the specific glass production value chain nodes require extensions to the original modeling framework.

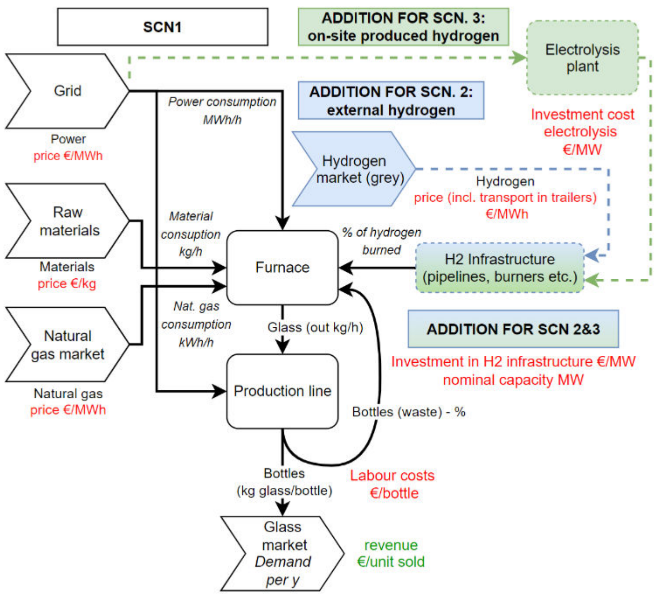

Figure 1 Schematics of the system analysed as a node and flow system.

In Figure 1, the nodes and arrows with black borders represent the baseline elements, common to all three cases. Nodes with arrow shapes denote Markets, while those with square forms represent Plants. Additional nodes for cases 2 and 3 are depicted in blue and green, respectively, and nodes requiring investments are indicated with dashed lines. Main cash flows are depicted in the figure, either as costs (in red) or as revenues (in green). The first additional node type refers to the furnace responsible for melting raw materials into liquid glass in a glass production facility. It requires electricity for ventilation and additional temperature support, core raw materials to form the glass, and natural gas to provide the necessary heat for the melting process.

The furnace node can be formulated with the following equations:

$$Capacity^{furnace,t} = flow_{out}^{furnace,glass,t}, \forall t \in T \quad (1)$$

$$\frac{1}{P} flow_{in}^{furnace,power,t} \geq \frac{1}{L} flow_{out}^{furnace,glass,t}, \forall t \in T \quad (2)$$

$$\frac{1}{RM} flow_{in}^{furnace,RM,t} \geq \frac{1}{L} flow_{out}^{furnace,glass,t}, \forall t \in T \quad (3)$$

$$\frac{1}{NG} flow_{in}^{furnace,NG,t} \geq \frac{1}{L} flow_{out}^{furnace,glass,t}, \forall t \in T \quad (4)$$

where the variable $flow_{in}$ denotes the inflows of power, raw materials (RM), and natural gas (NG) required to produce a certain outflow of glass in the variable $flow_{out}$. The total amounts of power, raw materials and natural gas to produce L kilograms of glass are defined as the parameters P, RM, and NG respectively in the equations above. The outflow of glass from the furnace is represented as the capacity usage of the node with the variable $Capacity^{furnace,t}$. The model supports investments in capacity expansion with some associated capital expenditures (CAPEX).

Another type of node necessitating further modeling closely resembles the previous node, namely the hybrid furnace capable of burning both hydrogen and natural gas. It employs the same equations as the standard glass furnace, except for the final equation concerning the flow balance of natural gas and glass. This equation is replaced by the following two equations:

$$\frac{1}{G}\left(flow_{in}^{furnace,NG,t} + flow_{in}^{furnace,H_2,t}\right) \geq \frac{1}{L} flow_{out}^{furnace,glass,t}, \forall t \in T \quad (5)$$

$$\left(\frac{H_{2,\%}}{1 - H_{2,\%}}\right) flow_{in}^{furnace,NG,t} = flow_{in}^{furnace,H_2,t}, \forall t \in T \quad (6)$$

where the parameter G denotes the nominal total gas consumption of the furnace (of hydrogen and natural gas combined in MWh), and $H_{2,\%}$ represents the parameter determining the percentage of energy consumption of the furnace gas consumption that is covered by hydrogen.

The third type of node which requires additional modelling pertains to the production lines in a glass factory. It accounts for waste involved in the forming process of bottles and also the associated costs with personnel and electricity. The following equations define the production lines within the model:

$$\frac{1}{B} flow_{in}^{Lines,glass,t} = \frac{1}{(1-W)} flow_{out}^{Lines,bottles,t}, \forall t \in T \quad (7)$$

$$\frac{1}{P} flow_{in}^{Lines,power,t} = \frac{1}{(1-W)} flow_{out}^{Lines,bottles,t}, \forall t \in T \quad (8)$$

$$\mathrm{OPEX}^{\mathrm{Lines,t}} = \frac{1}{W} * C * flow_{out}^{Lines,bottles,t}, \forall t \in T \quad (9)$$

$$Capacity^{Lines,t} = flow_{out}^{Lines,bottles,t}, \forall t \in T \quad (10)$$

The inflows, denoted by the variable $flow_{in}$, are associated with the liquid glass entering the forming molds and power consumption. The outflow of bottles, denoted by $flow_{out}^{Lines,bottles,t}$, represents the number of bottles produced in the production lines over time. Parameters to the equations include the bottle weight (B), production waste (W), and labor cost (C). The capacity usage of the lines, represented by $Capacity^{Lines,t}$, corresponds to the total outflow of bottles from the line over time.

3.2 Input data

The input data utilized for the simulation and analysis are presented in Table 1.

Table 1. Input data for the simulation.

Parameter	Value	Unit
Discount rate	5	%
Number of strategic periods	6	-
Duration of strategic periods	1	year
Number of operational periods	24	-
Duration of operational periods	1	hour
Nat. gas costs	50-70	EUR/MWh
Power costs	150-180	EUR/MWh
Raw Material costs	180-230	EUR/ton
Grey hydrogen costs	500-750	EUR/MWh
Income final product	1-5	EUR/unit
Final product demand	600-800	Units/hour
Furnace capacity	150-350	kg glass/h
Natural gas consumption	2700-3200	kWh/h
Power consumption	25-40	kWh/h
Energy replaced by H2 in the furnace	30-50	% (energy)
Production line capacity	1000-1500	Units/h
Weight bottle units	0.15-0.4	kg/unit
Production line waste	20-60	% of final units
Production line power consumption	50-80	kWh/h
Investment costs hydrogen infrastructure	300-700	EUR/MW
Investment costs electrolysis plant	1800-2500	EUR/MW
Electrolysis plant efficiency	50-80	% LHV

3.3 Scenario definition

This section presents the scenarios analyzed for the impact of hydrogen in glass production.

Scenario 1, titled "Baseline," comprises three Market nodes supplying electricity, raw materials, and natural gas to the plant. The factory itself is then modeled with two Plant nodes: one representing the furnace, where raw materials are processed into molten glass using electricity and natural gas, and the other representing the production line, where the molten glass is processed into bottles using electricity. These bottles are subsequently sent to the Market node "Glass market," where demand is assigned and compelled to be met.

Building upon Scenario 1, two additional cases investigate the impact of hydrogen use.

Scenario 2, labeled "External Hydrogen," involves grey hydrogen provided externally as a service, modeled as a Market node that consolidates all related costs into a single levelized cost of hydrogen covering all expenses (production, transport, etc.).

Scenario 3, termed "On-site Produced Hydrogen," entails the production of hydrogen on-site by an electrolysis plant connected to the local grid.

Common to these two hydrogen cases is the infrastructure required to burn hydrogen in addition to natural gas at the furnace. This infrastructure includes the installation of pipelines in the factory and the replacement of some burners to cover 40% of the gas demand at the furnace in terms of energy content.

These three cases will be compared under identical conditions: the same final product demand and time structure, consisting of 6 strategic periods lasting one year each, with each operating period represented by 24 one-hour periods, equivalent to one day. However, the assumptions in this initial analysis are presented as constant values for the glass production facility.

4. Results and discussion

Ensuring the system meets the demand for the final product (bottle) is crucial for maintaining comparability of economic outcomes across the three scenarios.

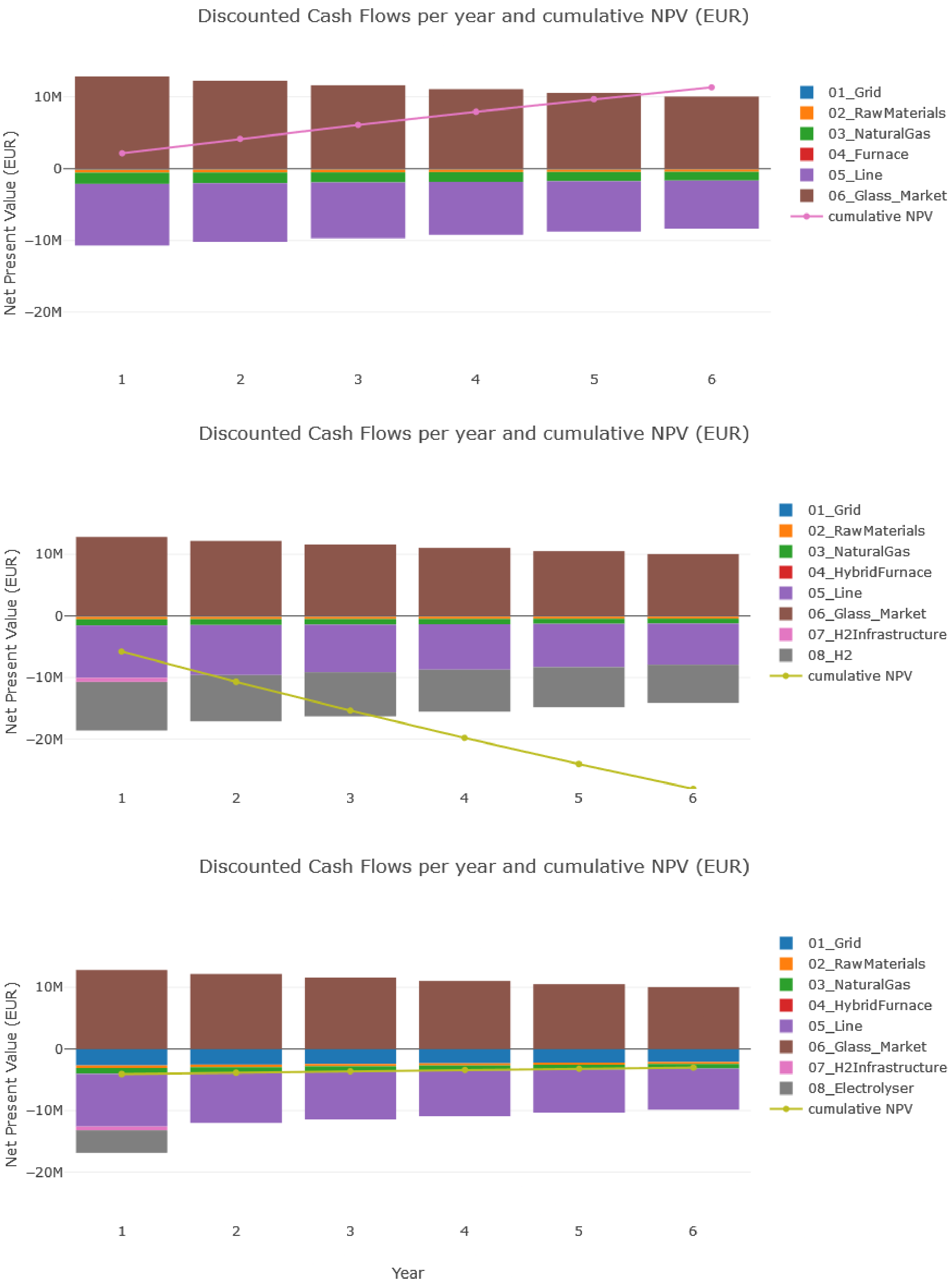

Figure 2 Yearly cash flow per node and cumulative NPV for the whole system for the Baseline (top), External Hydrogen (middle) and On-site Produced Hydrogen (below) cases with the assumed input data.

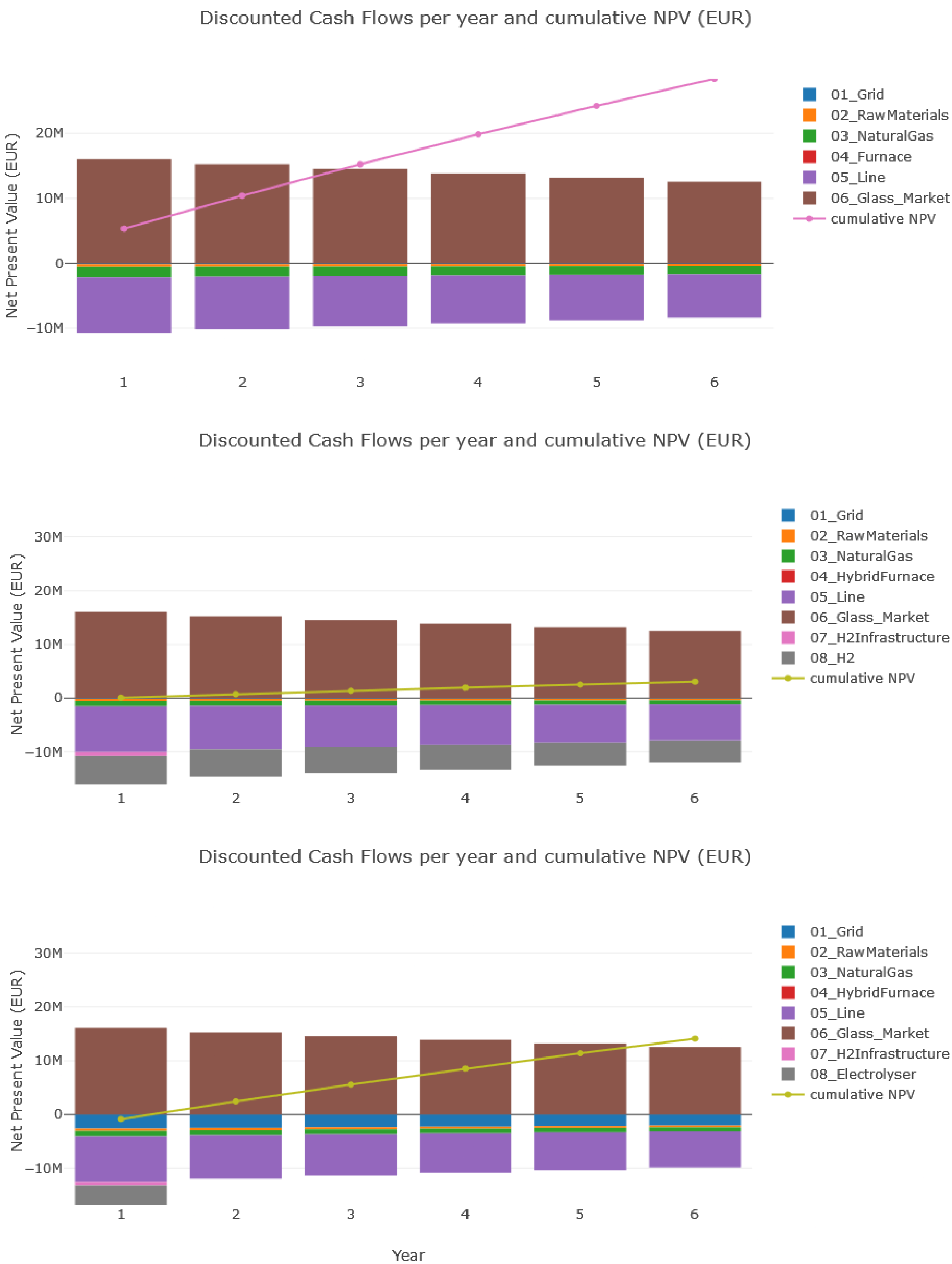

Figure 3 Yearly cash flow per node and cumulative NPV for the whole system for the Baseline (top), External Hydrogen (middle) and On-site Produced Hydrogen (below) cases with the modified input data to guarantee a positive NPV for all three cases.

This approach prevents the model from ceasing production in scenarios where a positive Net Present Value (NPV) isn't attained.

Figure 2 illustrates the yearly cash flows per node and cumulative NPV of the three scenarios using the data input in section 3.2. Notably, the Baseline scenario is the only profitable one, achieving a NPV of 11.34 million EUR in year 6. Introducing hydrogen as a replacement for 40% of the natural gas results in negative NPV under the current assumptions. Among the hydrogen scenarios, external hydrogen delivery yields the poorest NPV (-28 million EUR in year 6), while on-site hydrogen production approaches break-even with a NPV of -3 million EUR in year 6, though it does not reach it.

A significant distinction between the Baseline scenario and Scenarios 2 and 3 is that the former does not involve any investment. Therefore, the NPV is determined solely by the difference between income and operational expenditure cash flows. Given that the data originates from an existing use case of the project, already deemed cost-effective, the cumulative NPV remains positive from the beginning of the horizon.

In Scenario 2, "External Hydrogen," the need to install hydrogen infrastructure and hydrogen burners to cover 40% of the furnace's energy, along with the operational costs of external hydrogen supply, significantly contribute to expenses. Hydrogen costs exceed those of grid electricity and natural gas by a considerable margin. In Scenario 3, "On-site Produced Hydrogen," a larger initial investment is evident, encompassing hydrogen infrastructure and an electrolysis plant. Grid costs also rise considerably, leading to higher energy operational costs compared to the Baseline scenario. Despite this, the economic outcomes of Scenario 3 surpass those of Scenario 2, with the NPV remaining relatively stable instead of progressively declining.

Given the current results, one might contemplate measures to render the hydrogen alternatives cost-effective. For this analysis, a simple measure involves increasing bottle revenue by 25%. Additionally, for Scenario 2, a reduction in the external hydrogen delivery price—currently over 10 times the cost of natural gas—by 33% results in a positive NPV. The updated results following these adjustments are depicted in Figure 3.

Predictably, the results of the Baseline scenario witness a significant improvement, with increased revenue contributing to its profitability, yielding a NPV of 28.43 million EUR in year 6.

In the scenario of Scenario 2, "External Hydrogen," the combined effect of the 33% reduction in external hydrogen price and the 25% increase in revenue render the scenario marginally profitable, with a positive NPV maintained throughout the horizon, albeit around 3 million EUR by the end. Hydrogen costs still dominate expenses, accounting for 62% of labor costs and even surpassing investment costs in hydrogen infrastructure.

For Scenario 3, "On-site Produced Hydrogen," the cumulative NPV starts negatively in the first year (-850 thousand EUR), but steadily rises to 14 million EUR by the 6th year. This initial negative balance is attributable to the investment in hydrogen infrastructure and the electrolysis plant.

This study shows that replacing current fossil gas with hydrogen in glass production poses challenges for achieving profitability. Despite low CO_2 taxes and favorable fossil gas prices, this production remains quite profitable. Most glass production cannot immediately switch to 100% hydrogen due to high energy consumption. Transitioning to 100% hydrogen would require even larger electrolyzers or robust supply chains capable of daily hydrogen delivery by trucks. These alternatives currently have a low likelihood of being applied in the next few years, according to the use. Therefore, this study aimed to investigate realistic scenarios and empirical related scenarios. However, a transition to 40% hydrogen integration already reveals the current profitability limits of glass production with hydrogen.

Scenarios 2 and 3 could be profitable if the market demand for low-carbon footprint bottles significantly increases in the next few years. Being an early adopter in the glass market can help gain a strong market share and make the transition profitable.

However, the significant investment required for electrolyzers remains a major concern. Nevertheless, a reduction in electrolyzer costs is not anticipated in the next year [17]. With growing demand for electrolyzers and lengthy delivery times, it is expected that costs will either remain stable or potentially increase in the years ahead.

Conclusion

The European glass industry is increasingly exploring hydrogen as a sustainable option. However, understanding the economic implications of different delivery and implementation methods is crucial for this transition. This study contributed to the development of a simulation model using empirical data from a case study, analyzing the cost implications of various hydrogen delivery and implementation methods in glass production, and providing insights about costs and profitability. However, currently, glass production is profitable, but transitioning to hydrogen incurs high costs. External incentives are necessary to drive further decarbonization in the industry, whether through reductions in electrolyzer prices, hydrogen delivery costs, or significant increases in CO_2 taxes. However, scenarios involving increased CO_2 taxes have not been thoroughly explored. Thus, future research should investigate how other contextual factors could make glass production with hydrogen profitable and identify the necessary external incentives.

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