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Hydrogen Value Chain Optimization for Decarbonization of the Glass Industry in Europe: A Case Study ⋆

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Abstract: The European Union's ambitious carbon reduction targets for 2030 demand innovative solutions across energy-intensive sectors. Among these, the glass industry is actively seeking sustainable alternatives to natural gas combustion, a major source of carbon emissions in glass production. This paper investigates the potential of hydrogen as a decarbonization pathway for the glass industry, focusing on a use-case from a glass manufacturing facility in Europe. To address these emissions, this study explores the replacement of conventional fuels with hydrogen, a promising clean fuel alternative. Hydrogen not only offers a pathway to substantial carbon reduction but also aligns well with the glass industry's operational requirements for high temperature processes. However, the transition requires a strategic approach to the hydrogen value chain, ensuring an optimized supply, storage, and distribution network. This paper discusses the techno-economic and environmental aspects of hydrogen integration in glass manufacturing, emphasizing hydrogen production, delivery, and utilization frameworks that enhance cost-effectiveness and sustainability in the value chain. Through this lens, we aim to provide a viable roadmap for hydrogen adoption within the glass industry, offering insights into the broader implications for sectoral decarbonization across Europe.

Keywords: Value chain optimization; Hydrogen; Glass Industry; Energy-intensive industries; Decarbonization

1. INTRODUCTION

Industries account for 30% of global energy use and 20% of carbon emissions, yet their adoption of renewables lags behind (Nurdiawati and Urban, 2021). Decarbonizing energy-intensive sectors, such as the glass industry, is critical for achieving climate goals (Wyns and Axelson, 2016). However, the glass industry faces significant challenges due to its reliance on fossil fuels for high-temperature processes.

To meet the European Union's ambitious 2030 targets, transformative solutions such as hydrogen, electrification, and carbon capture are essential (Kulovesi and Oberthür, 2020; Del Rio et al., 2022). Hydrogen is a promising alternative for glass production but faces technical and economic barriers (Tseng et al., 2005). With diverse subsectors and a strong dependence on fossil fuels, the industry struggles to achieve full decarbonization by 2050 (Del Rio et al., 2022).

The EU-funded H2GLASS project aims to revolutionize hydrogen adoption in glass production. Preliminary cost assessments were reported in Fragapane et al. (2024). This work integrates pilot data with advanced modeling, using `EnergyModelsX` to analyze hydrogen value chains technically and economically. A comprehensive Life cycle assessments (LCA) evaluates environmental impacts across the value chain, ensuring decarbonization with minimal trade-offs. The main contributions of this paper are :

- A mathematical model optimizing hydrogen-natural gas blends, hydrogen burner investments, electrolysis expansion, and external hydrogen supply.
- Optimizes both strategic investments and operational plant settings.
- Techno-economic analysis of onsite electrolysis vs. truck-delivered hydrogen under various CO2 allowance scenarios.
- LCA of decarbonization strategies to assess hydrogen adoption's environmental impact in glass manufacturing.

Leveraging insights from the H2GLASS project, computational tools like `EnergyModelsX`, and findings from the LCA, this paper explores the feasibility of hydrogen as a decarbonization pathway for the glass industry. By examining the hydrogen value chain, the study highlights strategies for maximizing sustainability and cost-effectiveness while addressing practical constraints.

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Table 1. Notations

EMX variable	Description
$c^{\text{inst}}_{n,t}$	Capacity in node n at time t.
$c^{\text{use}}_{n,t}$	Used cap. in node n at time t.
$q^{\text{in}}_{n,t,p}$	Inflow of prod. p to node n at time t.
$q^{\text{out}}_{n,t,p}$	Outflow of prod. p from node n at time t.
$\text{opex}^{\text{fix}}_{n,t}$	Fixed OPEX in node n at time t.
$\text{opex}^{\text{var}}_{n,t}$	Varying OPEX in node n at time t.
$\text{capex}_{n,t}$	CAPEX in node n at time t.
$\text{capex}^{\text{tot}}$	Total capex for the project.
$\text{emit}^{\text{CO2}}_{t}$	Total CO_2 emissions at time t.
GlassEMX var.	**Description**
$c^{\text{inst,AF}}_{n,t}$	Capacity of alt. fuel in furnace n at time t.
$c^{\text{use,AF}}_{n,t}$	Used cap. of alt. fuel in furnace n at time t.
$c^{\text{add,AF}}_{n,t}$	Added cap. of alt. fuel in furnace n at time t.
$\text{capex}^{\text{AF}}_{n,t}$	CAPEX of alt. fuel in furnace n at time t.
$\text{def}^{\text{sink}}_{n,t}$	Deficit of the market n's demand at time t.

2. METHODOLOGY

`EnergyModelsX` (EMX) (Hellemo et al., 2024) is a `Julia`-based framework for optimizing multi-carrier energy systems at regional and larger scales. Built on `JuMP`, it models generation, storage, and networked technology nodes, ensuring flexibility while maintaining core system integrity.

EMX integrates TimeStruct (Flatberg and Hellemo, 2024) for multi-horizon time modeling, capturing short-term operations and long-term planning while managing resource flows and uncertainties. The framework also supports investment modeling with discrete, semi-continuous, or continuous options, enabling analysis of infrastructure changes and trade-offs in cost, emissions, and reliability. By default, the model minimizes operational costs, extending to investment expenditures when expansion is considered.

2.1 Modeling and Mathematical Formulation

The model represents the energy system using nodes and edges, capturing technologies, energy carriers, and products. It operates on a two-level time framework: a strategic level for investment and capacity decisions and an operational level for system performance and cost evaluation. Nodes include input nodes for resources (natural gas, hydrogen, power, etc.), market nodes for products (glass, molten glass, waste glass), and plant nodes for transformation processes like furnaces and production lines. Emission nodes track environmental impacts, particularly CO_2 emissions.

The optimization framework, formulated as a mixed-integer programming (MIP) problem, aims to maximize Net Present Value (NPV) by balancing investment costs, operational expenses, and revenue. Decision variables are categorized into strategic investment choices and operational parameters, detailed in Table 1. While market nodes follow the EMX framework, glass production requires additional model extensions. In what follows, we present the main constraints of the general EMX framework used to address the optimization problem in this paper.

CAPACITY CONSTRAINTS

The capacity utilized in node n at time t is restricted by its installed capacity:

$$c^{\text{use}}_{n,t} \leq c^{\text{inst}}_{n,t}, \quad \forall n \in \mathcal{N},\, t \in \mathcal{T}^{\text{inv}} \tag{1}$$

where $\mathcal{N}$ represents the set of all nodes, and $\mathcal{T}^{\text{inv}} \subseteq \mathcal{T}$ denotes the subset of strategic time periods when investments are considered.

The installed capacity $c^{\text{inst}}_{n,t}$ is determined by a user-defined function, $\text{capacity}(n,t)$:

$$c^{\text{inst}}_{n,t} = \text{capacity}(n,t), \quad \forall n \in \mathcal{N},\, t \in \mathcal{T}^{\text{inv}} \tag{2}$$

This function specifies how the capacity of equipment or processes is calculated or expanded, while $c^{\text{inst}}_{n,t}$ represents the actual capacity available in the model.

Flow Constraints: The inflow of product p into node n at time t is defined as:

$$q^{\text{in}}_{n,t,p} = \hat{I}(n,p) \times c^{\text{use}}_{n,t}, \quad \forall n \in \mathcal{N},\, t \in \mathcal{T},\, p \in \mathcal{I}(n) \tag{3}$$

Here, $\mathcal{I}(n)$ is the subset of products $p \in \mathcal{P}$ that are inputs to node n, and $\hat{I}(n,p)$ is a function specifying the inflow requirements of the product based on the node's capacity. This allows for defining specific recipes or inflow rates needed for manufacturing.

Similarly, the outflow of product p from node n at time t is:

$$q^{\text{out}}_{n,t,p} = \hat{O}(n,p) \times c^{\text{use}}_{n,t}, \quad \forall n \in \mathcal{N},\, t \in \mathcal{T},\, p \in \mathcal{O}(n) \tag{4}$$

where $\mathcal{O}(n)$ represents the subset of products that are outputs from node n, and $\hat{O}(n,p)$ defines the outflow rates proportional to the node's capacity.

Cost and Cashflow Constraints

Fixed Operating Expenditures: Fixed operational costs are aggregated over strategic periods:

$$\text{opex}^{\text{fix}}_{n,t} = \widehat{opf}_{n,t}(n,t) \times c^{\text{inst}}_{n,t}, \quad \forall n \in \mathcal{N}^{\text{inv}},\, t \in \mathcal{T}^{\text{inv}} \tag{5}$$

Here, $\text{opex}^{\text{fix}}_{n,t}$ represents the fixed operating costs of node n during the strategic period t, while $\widehat{opf}_{n,t}(n,t)$ is a function defining these expenditures as a function of installed capacity and scaled according to the installed capacity in the node. Notice that $\mathcal{N}^{\text{inv}} \subseteq \mathcal{N}$ is a subset of nodes that allow investments.

Variable Operating Expenditures: Varying operational costs are calculated as:

$$\text{opex}^{\text{var}}_{n,t} = \sum_{t_{\text{inv}} \in \mathcal{T}^{\text{inv}}} \widehat{opv}(n, t_{\text{inv}}) \times c^{\text{use}}_{n,t_{\text{inv}}} \times \widehat{sc}(t_{\text{inv}}, t), \tag{6}$$

Here, $\widehat{opv}(n,t)$ calculates the variable costs, while $\widehat{sc}(t_{\text{inv}},t)$ represents a scaling factor to account for operational scenarios and representative periods. This factor can also consider potential operational scenarios and their profitability in representative periods.

Capital Expenditures (CAPEX): A separate package is used when considering investments, i.e., *EnergyModelsInvestments*. In this module, additional cost variables are introduced to extract the cost of investments in an element at each investment period. The overall capital expenditure, $\text{capex}^{\text{tot}}$, considers the invested capacity for calculating the total costs and the terminal value of individual technologies as follows:

$$\text{capex}^{\text{tot}} = \sum_{n\in\mathcal{N}^{\text{inv}}} \sum_{t\in\mathcal{T}^{\text{inv}}} \text{capex}_{n,t}, \tag{7}$$

where $\text{capex}_{n,t}$ is the undiscounted total CAPEX of node n with investments in investment period t. The CAPEX of a node is determined based on the investments in the node related to capacity expansion:

$$\text{capex}_{n,t} = \widehat{capex}(n,t) \times c^{\text{add}}_{n,t}, \quad \forall n \in \mathcal{N}^{\text{inv}}, t \in \mathcal{T}^{\text{inv}} \tag{8}$$

where $c^{\text{add}}_{n,t}$ is the capacity added to node n at time period t, and $\text{capex}_{n,t}$ is a function that calculates the corresponding CAPEX if an investment in capacity expansion occurs in the node.

Emissions: Emissions, such as CO_2 , are modeled through a specific resource type, *ResourceEmit*. Each node n can specify the corresponding emission data in case there are emissions which will then be denoted by $\text{emit}^{\text{CO2}}_{n,t}$. The total system emissions for resource p, such as CO_2 , are calculated as:

$$\text{emit}^{\text{CO2}}_t = \sum_{n\in\mathcal{N}} (\sum_{p\in\mathcal{P}} q^{\text{in}}_{n,t,p} \times \text{E}^{Int}_p + c^{\text{use}}_{n,t} \times \text{E}_{n,\text{CO2}}), \quad \forall t \in \mathcal{T} \tag{9}$$

Where E^{Int}_p represents the carbon intensity of a resource p when used in a node n (e.g. combustion of NG in the furnace), and $\text{E}_{n,\text{CO2}}$ are the CO_2 process emissions of a node n, representing in this case upstream emissions, e.g. carbon intensity of H_2delivered by trucks. The total emissions of a resource at time t, such as CO_2 , are limited by a total emission constraint as follows:

$$\text{emit}^{\text{CO2}}_t \leq \text{emit}^{\text{CO2,max}}_t, \forall t \in \mathcal{T}. \tag{10}$$

2.2 GlassEMX

The GlassEMX package bridges the gap between the generic EMX framework and the specific requirements of glass manufacturing. It introduces specialized nodes, variables, and constraints that enable detailed modeling of fuel usage, production processes, and emission reduction strategies. A key innovation in GlassEMX is the Fuel Furnace Node, which focuses specifically on the replacement of burners using traditional natural gas (NG) combustion to H_2-based alternatives in glass manufacturing.

The Fuel Furnace node serves as the decision-making point for modeling H_2 adoption, capturing the technical, economic, and operational complexities associated with fuel substitution. A critical aspect of this node is determining the optimal blend of H_2 and NG provided to the furnace, which involves replacing NG burners with hydrogen-based burners.

This node integrates both operational and investment aspects of glass production. Operational decisions include maintaining consistent glass quality and production throughput with a specific gas blending, while investment decisions involve capital expenditures for replacing NG burners with H_2 burners, installing hydrogen pipelines, and installation of electrolyzers for onsite hydrogen production.

A mathematical formulation is presented for the Fuel Furnace (FF) node using mixed-integer programming (MIP). The additional variables are shown in Table 1, under Glass EMX. The main additional parameters are the following:

- p^m: The primary fuel type used at node n, in this case NG.
- p^{alt}: The alternate fuel type used at node n, in this case H_2.
- $\hat{I}^g(n)$: Gas ratio is a function specifying the inflow requirements of the gas blend (in Low Heating Value energy flow) based on the furnace n's capacity.

Flow balance equations are defined for all furnace nodes follows equation (3), except for all furnaces $n \in \mathcal{N}^{\text{FF}}$, $t \in \mathcal{T}$ and product $p \in \mathcal{P} : p \notin \{\text{p}^m, \text{p}^{alt}\}$. Note that $\mathcal{N}^{\text{FF}} \subseteq \mathcal{N}$ is a subset of nodes that are glass Fuel Furnaces. The flow of each fuel p into node n at time t is determined by the utilized capacity and the input ratio.

Fuel balance equations are then defined for all $n \in \mathcal{N}^{\text{FF}}, t \in \mathcal{T}$

$$c^{\text{use}}_{n,t} \times \hat{I}^g(n) = q^{\text{in}}_{n,t,\text{p}^m} + q^{\text{in}}_{n,t,\text{p}^{alt}} \tag{11}$$

The total utilized capacity, scaled by the gas ratio, is equal to the sum of the flows from the main and alternate fuels. The usage of alternate fuel is defined as follows:

$$c^{\text{use,AF}}_{n,t} = q^{\text{in}}_{n,t,\text{p}^{alt}} \quad \forall n \in \mathcal{N}^{\text{FF}}, t \in \mathcal{T} \tag{12}$$

The capacity utilized for alternate fuel is equal to the flow of alternate fuel into the node. The upper flow limit of the main fuel is defined as follows for all: $n \in \mathcal{N}^{\text{FF}}, t \in \mathcal{T}$:

$$q^{\text{in}}_{n,t,\text{p}^m} \leq c^{\text{inst}}_{n,t} \times \hat{I}^g(n) - c^{\text{inst,AF}}_{n,t} \tag{13}$$

The flow of the main fuel is constrained by the installed capacity, scaled by the gas ratio, minus the capacity allocated to the alternate fuel.

The following constraints define the relationship between fuel usage, installed capacities, and alternate fuel limitations within the optimization model. In addition to equation (1), which also applies to the furnace, the usage of alternate fuel cannot exceed the installed alternate fuel capacity.

$$c^{\text{use,AF}}_{n,t} \leq c^{\text{inst,AF}}_{n,t} \quad \forall n \in \mathcal{N}^{\text{FF}}, t \in \mathcal{T} \tag{14}$$

Alternate fuel capacity is limited by a fraction of the total installed capacity, based on the gas ratio:

$$c^{\text{inst,AF}}_{n,t} \leq \hat{I}^g(n) \times c^{\text{inst}}_{n,t} \quad \forall n \in \mathcal{N}^{\text{FF}}, t \in \mathcal{T} \tag{15}$$

The CAPEX of the burners is determined based on the investments in the node related to capacity expansion:

$$\text{capex}^{\text{AF}}_{n,t} = \widehat{capex}^{\text{AF}}(n,t) \times c^{\text{add,AF}}_{n,t} \quad \forall n \in \mathcal{N}^{\text{inv}}, t \in \mathcal{T}^{\text{inv}} \tag{16}$$

Where $\widehat{capex}^{\text{AF}}(n,t)$ is a function defining the alternative fuel burner investment costs for the Fuel Furnace n in time t. Finally, a slight change to the objective function is required to account for the blend of fuels in the new node:

$$f_{\text{obj, new}} = f_{\text{obj}} - \sum_{n\in N^{\text{FF}}, t\in\mathcal{T}^{\text{inv}}} \omega_{n,t} \times \text{capex}^{\text{AF}}_{n,t} \tag{17}$$

where $\omega_{n,t}$ is the scaling factor for the objective also including the discount factor, and $\text{capex}^{\text{AF}}_{n,t}$ is the capital expenditures associated with the required investments to deploy the H_2burners at the Furnace Fuel node.

Another critical component of GlassEMX is the Market Sink Node, which models the final stage of production—glass bottle output. This node integrates produc-

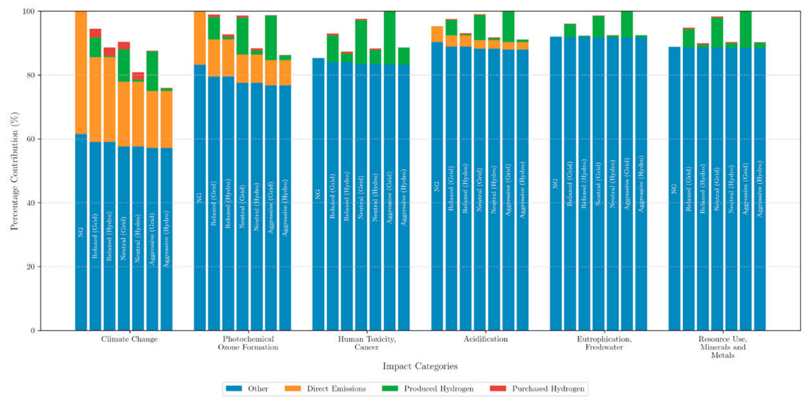

Fig. 1. LCA Impacts Contribution Analysis Comparing the TEA Scenarios 10-Year Average Production Profile.

tion with market dynamics, considering factors such as production quantity, demand, and pricing. By accurately capturing the output stage, the Market Sink Node ensures that production targets align with both market requirements and industry economic objectives, completing the modeling framework from raw material input to market-ready products.

A key characteristic of this market node is that $c^{\text{inst}}_{n,t}$ represents the market's demand, which is equal to the used capacity of the node (i.e., the actual delivered product), along with the deficit or difference between the market's demand and the fulfilled demand:

$$c^{\text{use}}_{n,t} + \text{def}^{\text{sink}}_{n,t} = c^{\text{inst}}_{n,t}, \quad \forall n \in \mathcal{N}^{\text{M}}, t \in \mathcal{T} \tag{18}$$

where $\mathcal{N}^{\text{M}} \subseteq \mathcal{N}$ is a subset of the nodes containing the market sink nodes of the system. The relation between penalty and revenue is represented as part of the variable OPEX, where revenue is modeled as a negative OPEX:

$$\text{opex\_var}_{n,t} = \sum_{t_{\text{inv}} \in \mathcal{T}^{\text{inv}}} (\text{def}^{\text{sink}}_{n,t} \times \widehat{\text{pen}}(n,t)$$
$$- c^{\text{use}}_{n,t} \times \widehat{\text{rev}}(n,t)) \times \widehat{sc}(t_{\text{inv}},t), \quad \forall n \in \mathcal{N}^{\text{M}}, t \in \mathcal{T} \tag{19}$$

where $\widehat{\text{rev}}(n,t)$ is the revenue obtained from delivering the required product to market n at time t, and $\widehat{\text{pen}}(n,t)$ is the penalty incurred for not fulfilling the demand for the same market n at time t.

3. CASE STUDY

This study applies the proposed methodology to a use case from the H2GLASS project, which explores hydrogen integration in glass manufacturing for decarbonization. The energy-intensive melting process, traditionally reliant on natural gas (NG), is a major source of emissions. Replacing NG with hydrogen (H_2) aims to reduce carbon emissions while maintaining process stability.

The study considers a 15-year strategic period with a 1-hour duration for both strategic and operational periods. Key cost parameters include natural gas ($30 - 60$ €/MW h), power ($30 - 100$ €/MW h), oxygen ($60 - 120$ €/t), raw materials ($80 - 120$ €/t), trailer hydrogen ($50 - 800$ €/MW h), and water ($0.1 - 0.8$ €/t). The furnace capacity ranges from ($3 - 4\text{t h}^{-1}$), with final product output between ($2500 - 3000\text{t h}^{-1}$). The final product cost is between ($800 - 1500$ €/t), while natural gas consumption ranges from ($2000 - 5000$kW), and power consumption is between ($1000 - 1500$kW). A 5% discount factor is considered in the analysis.

Key constraints include a carbon cap of $3000 - 1200000$t per period and an NG consumption limit of 1000000t. Carbon costs range from $90 - 110$ €/t (Commission, 2024; Brand et al., 2023), with projections accounting for evolving energy demand and policy shifts over 15 years (Gogia et al., 2019).

Hydrogen infrastructure costs range from $190000 - 500000$ €/MW, with a 50MW capacity cap per period. Electrolysis CAPEX is estimated at $570000 - 1500000$ €/MW. These estimates incorporate historical data and technological advancements, reflecting expected cost reductions.

The optimization model integrates these variables, including NG prices, carbon taxation, and emissions targets, to support strategic decisions on hydrogen investments.

4. LCA

LCA impacts are included to provide a comprehensive understanding of the fuel-switching scenarios in the glass factory, expanding upon the TEA model, which focuses on direct carbon emissions. The LCA quantifies carbon emission reductions along the value chain and identifies any burden shifting to upstream processes or other impact categories. The functional unit is 1 tonne of glass produced over a ten-year transition period.

The LCA assumes a static electricity grid mix and offers an initial approximation of the TEA scenarios. The LC inventory combines TEA outputs, literature, and the Ecoinvent database. The Environmental Footprint 3 impact method is used, focusing on categories relevant to the glass industry: Climate Change, Photochemical Oxidant Formation, Human Toxicity (Cancer), Acidification, Freshwater Eutrophication, and Resource Use (Minerals and Metals) (Belliard, 2023).

Material and energy flows from the TEA outputs form the basis of the LCA. Hydrogen demand is met by onsite PEM electrolysis and purchased hydrogen from steam methane reforming (Bareiß et al., 2019; Antonini et al., 2020). Direct emissions stem from natural gas use, while the "other" category includes embodied impacts from raw materials, electricity (excluding electrolysis), oxygen, water, waste, and natural gas supply.

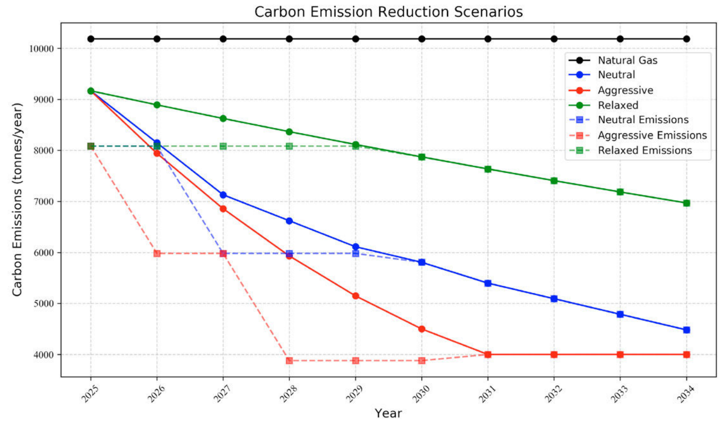

Fig. 2. Carbon emissions comparison (2025–2034) for Original, Aggressive, and Relaxed scenarios, illustrating the impact of different decarbonization strategies on emission reduction efforts.

The facility's electricity is currently sourced from hydropower, with a representative Ecoinvent inventory. Future electrolyser installations require large electricity amounts, ideally from this source, though two cases are considered: (1) the electrolyser relies on the national grid due to capacity constraints, and (2) the hydropower connection is expanded to meet demand, with each scenario distinguished by a 1 or 2 suffix.

5. RESULTS

This study evaluates three carbon reduction scenarios—Relaxed, Neutral, and Aggressive—assessing their impact on natural gas consumption, emissions, and economic performance from 2025 to 2034. Each scenario balances decarbonization speed, feasibility, and cost. The analysis is visualized through three plots: energy flows (Figure 4), emissions trajectories (Figure 2), and net present value (NPV) (Figure 3), highlighting the trade-offs between environmental impact and economic feasibility.

Key investment decisions, such as introducing new hydrogen burners, drive these trends. In the Relaxed Scenario, investments occur in 2025 and 2030, resulting in gradual energy mix changes and hydrogen adoption. Emissions decrease more slowly compared to other scenarios, as natural gas consumption remains high in the intermediate years. Economically, the Relaxed Scenario yields the highest cumulative NPV, prioritizing economic feasibility while delaying some environmental benefits.

The Neutral Scenario follows a linear decarbonization path, with investments in 2025, 2027, and 2030, accelerating hydrogen substitution gradually. Emissions decline consistently (Figure 2), balancing operational feasibility with EU goals. Economic performance (Figure 3) reflects moderate costs, yielding an NPV lower than the Relaxed but higher than the Aggressive Scenario. This steady approach minimizes disruptions while ensuring continuous progress.

In the Aggressive Scenario, earlier and more frequent investments in 2025, 2026, and 2028 drive rapid hydrogen adoption and emissions reductions (Figures 4 and 2). However, the higher upfront costs result in a lower cumulative NPV (Figure 3), emphasizing the trade-off between rapid decarbonization and financial strain.

A comparison shows a correlation between energy flows, emissions, and NPV. Faster hydrogen adoption leads to steeper emissions reductions but requires higher initial investments, impacting the NPV. The Relaxed Scenario defers investments for higher economic returns, while the Neutral Scenario achieves steady progress, and the Aggressive Scenario prioritizes environmental benefits.

These results highlight the importance of investment timing in balancing emissions reductions, economic viability, and infrastructure readiness, underscoring the need for integrated decision-making in decarbonization strategies.

5.1 *LCA Results*

The results in Figure 1 show that climate change impacts in the Aggressive scenario can be up to 25% lower than in the Relaxed scenario over ten years. However, reductions in factory emissions are partly offset by the upstream impacts of hydrogen production, with a 13% decrease if grid electricity is used for hydrogen production.

Photochemical Ozone Formation decreases by up to 13%, and Acidification by 4% with hydropower. However, Acidification increases with grid energy, while other categories like Human Toxicity, Freshwater Eutrophication, and Resource Use rise under grid energy (up to 17%, 8.5%, and 12.5%, respectively).

The "other" category dominates all impacts, suggesting limited reductions through fuel switching alone. For example, reusing oxygen from electrolysis could replace purchased oxygen, offering potential improvement.

These preliminary results confirm a reduction in carbon emissions, but other environmental impacts increase due to upstream electricity production. Future work will include dynamic electricity projections and incorporate LCA into an optimization framework, with multi-objective optimization considering costs and environmental impacts to generate improved scenarios (Silva et al., 2024).

6. CONCLUSION

This study evaluates hydrogen as a decarbonization pathway for the glass industry, analyzing three carbon reduc-

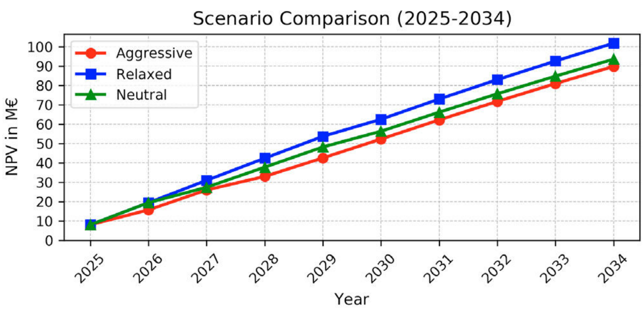

Fig. 3. NPV comparison (M€) from 2025 to 2034 for Aggressive, Relaxed, and Neutral strategies, showing expected trends over the decade.

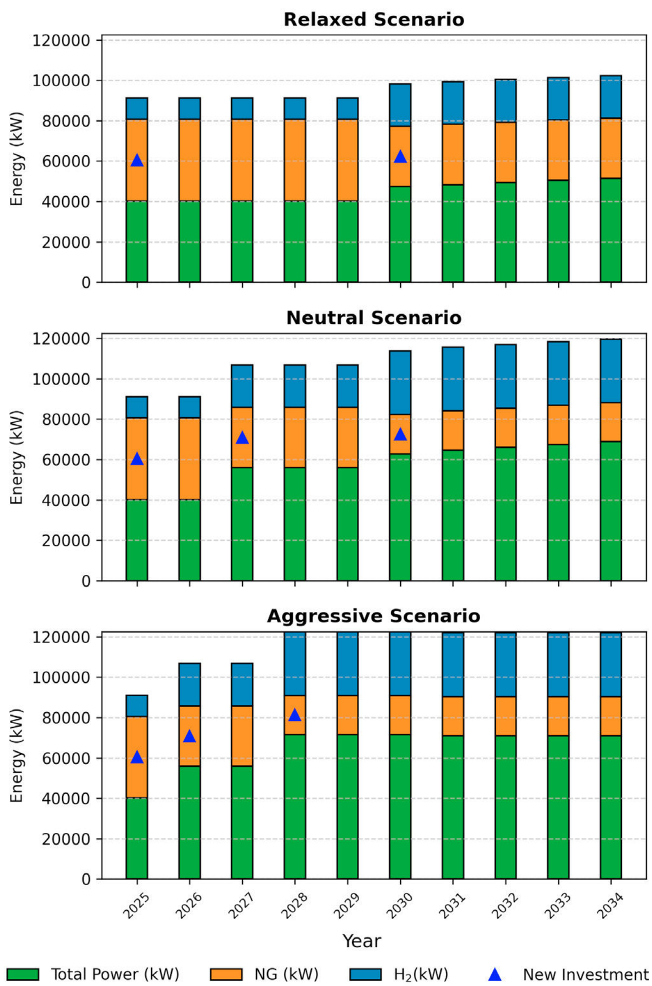

Fig. 4. Comparison of energy source contributions (Total Power, NG, and H_2) for three scenarios (Relaxed, Neutral, Aggressive) over the years 2025–2034.

tion scenarios—Relaxed, Neutral, and Aggressive. It highlights trade-offs between emissions reduction, economic performance, and operational feasibility.

By integrating life cycle assessment (LCA) insights, the findings offer strategic guidance for the glass sector and other energy-intensive industries. This research underscores hydrogen's role in global sustainability efforts, providing valuable insights for policymakers and industry leaders.

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