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Hydrogen supply design for the decarbonization of energy-intensive industries addressing cost, inherent safety and environmental performance

Giulia Fede [a,*], Giulia Collina [a,b], Alessandro Tugnoli [b], Marta Bucelli [c], Daniel F. Silva [d], Fabio Sgarbossa [a]

[a] Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology NTNU, Richard Birkelands vei 2B, 7034, Trondheim, Norway
[b] Department of Civil, Chemical, Environmental and Materials Engineering, Alma Mater Studiorum - Università di Bologna, via Terracini 28, 40131, Bologna, Italy
[c] Department of Gas Technology, SINTEF Energy Research, Kolbjørn Hejes vei 1A, 7034, Trondheim, Norway
[d] Department of Industrial and Systems Engineering, Auburn University, Auburn, AL, 36849, USA

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ABSTRACT

Through mathematical modeling, this paper integrates economic, safety, and environmental assessments to evaluate alternative hydrogen supply options (on-site production and external supply) and various hydrogen-based system configurations for decarbonizing energy-intensive industries. The model is applied to a case study in the glass sector. While reliance on natural gas remains the most cost-effective and safest solution, it does not align with decarbonization objectives. Assuming a complete hydrogen transition, on-site production reduces emissions by 85 % compared to current levels and improves safety performance over external supply. External supply of grey hydrogen becomes counterproductive, increasing emissions by 68 % compared to natural gas operations. Nevertheless, hydrogen cost rises from 3.6 €/kg with external supply to 4.2 €/kg with on-site production, doubling the fuel cost relative to natural gas. To address the trade-offs, the paper explores how specific constraints influence system design. A sensitivity analysis on key factors affecting hydrogen-related decisions provides additional support for strategic decision-making.

1. Introduction

In response to the threat of global climate change, the European Union (EU) has committed to the ambitious goal of achieving carbon neutrality by 2050, requiring comprehensive decarbonization strategies across all sectors. Among these, energy-intensive industries (EIIs) account for approximately 30 % of greenhouse gas emissions [1] and are particularly challenging to decarbonize. Sectors such as glass, steel, cement, and aluminum rely on high-temperature heat for raw-materials melting, currently sourced through natural gas combustion and consequently leading to substantial CO_2 emissions. Switching to alternative fuels at this stage has been identified as a promising decarbonization pathway [2]. Among the available options, hydrogen stands out due to its ability to provide high-temperature process heat while generating no direct carbon emissions. EU initiatives, such as H2GLASS [3] and HyInHeat [4], are actively demonstrating the feasibility of hydrogen integration in these industries.

However, the lack of hydrogen-related infrastructure in many such industries presents an obstacle [5], emphasizing the need for strategic decision-making. Critical considerations include estimating the required hydrogen capacity based on company-specific needs and targets and evaluating the optimal hydrogen supply strategy. These decisions must be supported by a comprehensive assessment that accounts for multiple performance factors influenced by hydrogen introduction, including economic feasibility, environmental impact, as well as safety performance [6].

Given the importance of maximizing production efficiency, the transition to hydrogen must be sufficiently cost-effective. This is challenged by hydrogen's higher cost compared to natural gas and its lower heating value, which increases the required volume to meet the same energy targets. Since hydrogen adoption is driven by decarbonization purposes, environmental performance must also be considered. While hydrogen combustion produces no direct emissions, different hydrogen types and supply alternatives can vary significantly in terms of indirect emissions. Additionally, due to the hydrogen's hazardous characteristics, such as the wide flammability range (4–75 %) and the low minimum ignition energy (0.02 mJ) [7], assessing safety performance is essential to ensure safe operations and implement effective risk

* Corresponding author.
E-mail address: giulia.fede@ntnu.no (G. Fede).

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mitigation strategies.

Table 1 provides an overview of relevant literature on hydrogen system design, not limited to applications in EIIs. It highlights whether the analysis conducted includes economic, safety, and environmental assessments. The table also shows, for each study, the application, distinguishing between supply chain network and industrial plant, and the sector of application. For studies focused on hydrogen system design at the industrial plant level, it is further specified whether alternative hydrogen supply options other than on-site production are considered. Most of these studies restrict their analysis to on-site hydrogen production. Among the few exceptions, Trapani et al. [8] consider external hydrogen supply only as a backup option, while Cvetkovska et al. [9] explore scenarios involving external supply but compare its performance to on-site production solely from an economic perspective. Moreover, as shown in Table 1, studies with an application at the industrial plant level typically focus on the economic and/or environmental aspects of hydrogen system design, while neglecting safety considerations. In contrast, the safety dimension is only addressed in studies applied at the supply chain network level. However, even in these cases, the safety assessments are limited to qualitative evaluations, lacking a quantitative approach that would provide more robust insights.

Conversely, the adoption of Inherently Safer Design (ISD) represents a cost-effective strategy for managing safety challenges at the early stages of process design [22], as it enables the identification of the safest design by systematically ranking alternatives according to their inherent hazards. The well-established methodology developed by Tugnoli et al. [23] pursues this objective through the evaluation of quantitative inherent safety performance indicators. Within the hydrogen domain, this methodology has already been applied to assess various hydrogen supply chain routes [24,25], different hydrogen storage systems [26], and, more recently, alternative fuel storage concepts for hydrogen-powered urban buses [27]. Nevertheless, to the best of our knowledge, its application for the design of on-site hydrogen supply systems has not yet been investigated.

The growing urgency for EIIs to decarbonize their operations, combined with the lack of research integrating safety assessments into the development of hydrogen infrastructure at the industrial plant level, represents the main motivation for this study. This paper aims to bridge the identified research gaps by proposing a mathematical model-based approach that evaluates alternative hydrogen supply options and various system design configurations at the industrial plant level, considering economic, safety and environmental dimensions. The glass manufacturing sector is used as a case study to show the application of the model and reach the ultimate goal of providing practitioners with insights to support strategic decision-making tailored to their specific requirements and the evolving external context. The main contributions of this work are:

- The integration of a quantitative inherent safety assessment into the strategic design of hydrogen-based systems for decarbonizing EIIs.
- The application of an inherent safety assessment methodology that is novel in the design of on-site hydrogen supply systems within manufacturing facilities.
- The evaluation of alternative hydrogen supply options (on-site production and external supply) and various hydrogen-based system configurations, in terms of cost, safety, and environmental performance through scenario analysis.
- The development of strategic design guidelines for hydrogen-based systems that account for potential constraints and requirements faced by companies.
- The inclusion of a sensitivity analysis to examine the influence of key external factors on hydrogen-based system design, ranging from commonly investigated variables such as electricity price and carbon intensity to less frequently explored factors like the type of externally supplied hydrogen.

The structure of the paper is as follows. Section 2 presents the methodology. Section 3 describes the system under investigation. Section 4 outlines the mathematical model for system components' behavior, as well as related costs, safety, and environmental performance. Section 5 explains the scenario analysis and describes the case study. Lastly, Section 6 presents and discusses the results, Section 7 summarizes the key findings and presents the strategic design guidelines for practitioners, and Section 8 highlights the limitations and future research directions.

2. Methodology

This paper employs a combination of quantitative methodologies to achieve the proposed research objective. Specifically, the methodological approach systematically integrates multiple established frameworks and methods to evaluate economic, inherent safety, and environmental performance across different system configurations, thereby supporting informed decision-making during the design stages. Fig. 1 illustrates a step-by-step schematic representation of the overall research methodology.

Step 0: System definition

The first step consists of defining a schematic representation of the system under investigation, including identifying the main modules, their functions, and the flows between them. It also establishes the reference scenario, representing the current operational configuration,

Table 1
Relevant literature on hydrogen system design.

Reference	Economic Assessment	Safety Assessment	Environmental Assessment	Application	Sector	Alternative H_2 supply
Barigozzi et al. [10]	✓	X	X	Industrial Plant	EII	X
Cvetkovska et al. [9]	✓	X	✓	Industrial Plant	EII	✓
De-León Almaraz et al. [11]	✓	✓	✓	Supply Chain Network	Transport	Not applicable
Erdoğan et al. [12]	✓	✓	✓	Supply Chain Network	Transport	Not applicable
Gärtner et al. [13]	✓	X	✓	Industrial Plant	EII, glass	X
Han et al. [14]	✓	✓	✓	Supply Chain Network	Not specified	Not applicable
Kim & Moon [6]	✓	✓	X	Supply Chain Network	Not specified	Not applicable
Marocco et al. [15]	✓	X	✓	Industrial Plant	EII, steel	X
Mukherjee et al. [16]	✓	✓	✓	Supply Chain Network	Microgrid	Not applicable
Ochoa Bique et al. [17]	✓	✓	✓	Supply Chain Network	Transport	Not applicable
Paudel & Choi [18]	✓	X	✓	Industrial Plant	Multiple EIIs	X
Röben et al. [19]	✓	X	✓	Industrial Plant	EII, copper	X
Sousa et al. [20]	✓	X	X	Industrial Plant	EII, ceramics	X
Superchi et al. [21]	✓	X	✓	Industrial Plant	EII, steel	X
Trapani et al. [8]	✓	X	✓	Industrial Plant	EII, semiconductor	✓
This study	✓	✓	✓	Industrial Plant	EII, glass	✓

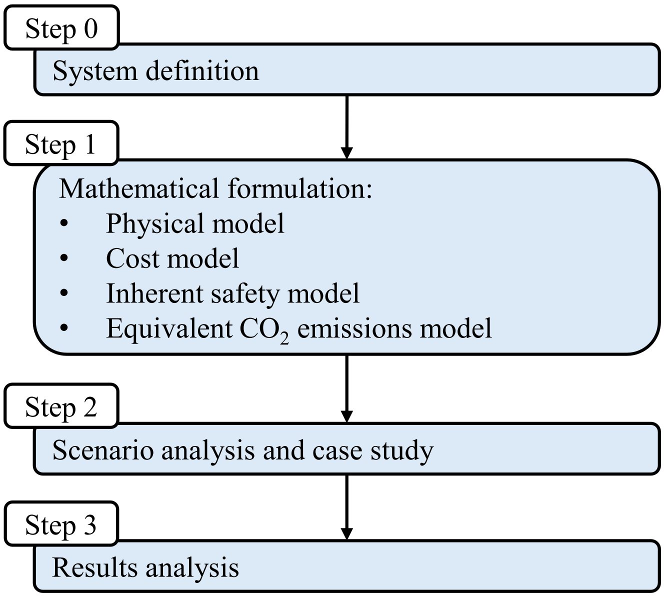

Fig. 1. Step-by-step schematic representation of the overall methodology adopted in the study. Details on Step 1 are provided in the Supplementary Material.

which serves as a baseline for comparing the performance of the hydrogen-based scenarios. The detailed system description is provided in Section 3.

Step 1: Mathematical formulation

This step develops the mathematical formulation describing the system's behavior and performance in terms of costs, inherent safety, and environmental impact, as presented in Section 4. The system's behavior is described through the physical model in Section 4.1, while the performance indicators are defined in Section 4.2. These indicators are derived from the corresponding cost, inherent safety and equivalent CO_2 emissions models, whose details are provided in the Supplementary Material. Importantly, the formulation is adapted to the reference scenario to enable comparison between current operations and hydrogen-based scenarios.

Step 2: Scenario analysis and case study

The scenario analysis evaluates multiple hydrogen-based system configurations by assigning different values to the model's decision variables. Rather than exploring all possible values and combinations, as is commonly done in the literature, the analysis focuses on commercially available solutions to ensure practical relevance. A real case study in the glass manufacturing sector demonstrates the multi-objective framework application. As a result, the analysis also accounts for a specific local context, providing insights that are grounded in a real-world scenario. Further details are provided in Section 5.

Step 3: Results analysis

The final step involves analyzing the results and assessing the performance of the various scenarios under investigation. Initially, the different hydrogen-based system configurations are compared without restrictions. To extend the analysis, potential external and internal constraints are introduced, including requirements commonly examined in similar studies, such as the hydrogen share in the fuel mix, as well as less explored constraints like the limited availability of renewable energy. A sensitivity analysis is also conducted on key factors influencing strategic decisions. Some of these align with existing literature, such as electricity price, while others bring a novel perspective to the analysis, including the type of externally supplied hydrogen. Ultimately, this step aims to identify trends, trade-offs, and key insights, providing a comprehensive framework to support the strategic design of hydrogen-based systems. A detailed discussion of the results is presented in Section 6.

3. System definition

The system definition is primarily based on a conceptual design developed for experimental hydrogen testing campaigns within the H2GLASS project [3]. Two hydrogen supply alternatives are considered: on-site production via electrolysis and high-pressure hydrogen gas delivery via trucks.

Fig. 2 schematically represents the system under investigation, highlighting the main modules: on-site hydrogen production through a Proton Exchange Membrane (PEM) electrolyzer (EL), hydrogen delivery via truck (TD), which requires storage (ST), and combustion in the furnace (CB).

The key variables characterizing each module are also highlighted in Fig. 2. The electrolyzer production module is defined by the power rating $P_{EL,R}$. Truck delivery involves truck-specific variables, which are the truck capacity C_{TR} and the hydrogen delivery pressure P_{TR}, as well as general variables, which are the maximum number of trucks unloading simultaneously B, and the truck arrival frequency λ. The storage tank is characterized by its volume V_{ST} and target storage pressure P_{ST}, which together determines the storage capacity C_{ST}, as well as the average level of hydrogen contained H_{2ST}. The combustion module is defined by the required percentage of hydrogen in the fuel mix $\%H_2$.

Referring to Fig. 2, the main flows are illustrated with arrows, while the dots indicate points of flow convergence. The electricity consumed by the electrolyzer P_{EL} is supplied either from the electrical grid P_{GR} or from renewable energy sources P_{RES}. H_{2EL} is the actual hourly hydrogen production by the electrolyzer, while H_{2TD} is the hourly hydrogen externally supplied. Together, they form the hourly hydrogen flow consumed by the furnace H_{2CB}. Remaining energy requirements are met through the hourly consumption of natural gas NG_{CB}.

The reference scenario can be derived from the described system definition. It represents the current operational setup, where combustion relies solely on natural gas. As a result, no hydrogen-related modules (EL, TD, ST) are present. The only module included is CB, represented by a required percentage of hydrogen in the fuel mix equal to 0. Similarly, the only relevant flow is the hourly consumption of natural gas, corresponding to the current natural gas demand. All variables and flows presented in the system definition are further detailed in the following section.

4. Mathematical formulation

This section presents the developed mathematical formulation. Section 4.1 provides the physical model, representing the system's behavior and flows. Building on this foundation, the models provided in the Supplementary Material are developed to assess the system performance in terms of cost, inherent safety and environmental impact. The corresponding performance indicators are formally defined in Section 4.2.

4.1. Physical model

Table 2, Tables 3 and 4 provide an overview of the mathematical notation used to represent the system. Specifically, Table 2 lists the decision variables, Table 3 presents the model outputs, and Table 4 outlines the model parameters.

4.1.1. Electrolyzer production module

The overall hydrogen demand by the furnace can be covered using different hydrogen supply alternatives. One option is on-site hydrogen production through water electrolysis using a Proton Exchange Membrane (PEM) electrolyzer. The nominal hourly hydrogen flow is estimated as in (1).

$$H_{2EL,N} = \frac{P_{EL,R} \cdot 1000 \cdot \eta_{EL}}{LHV_{H_2}} \tag{1}$$

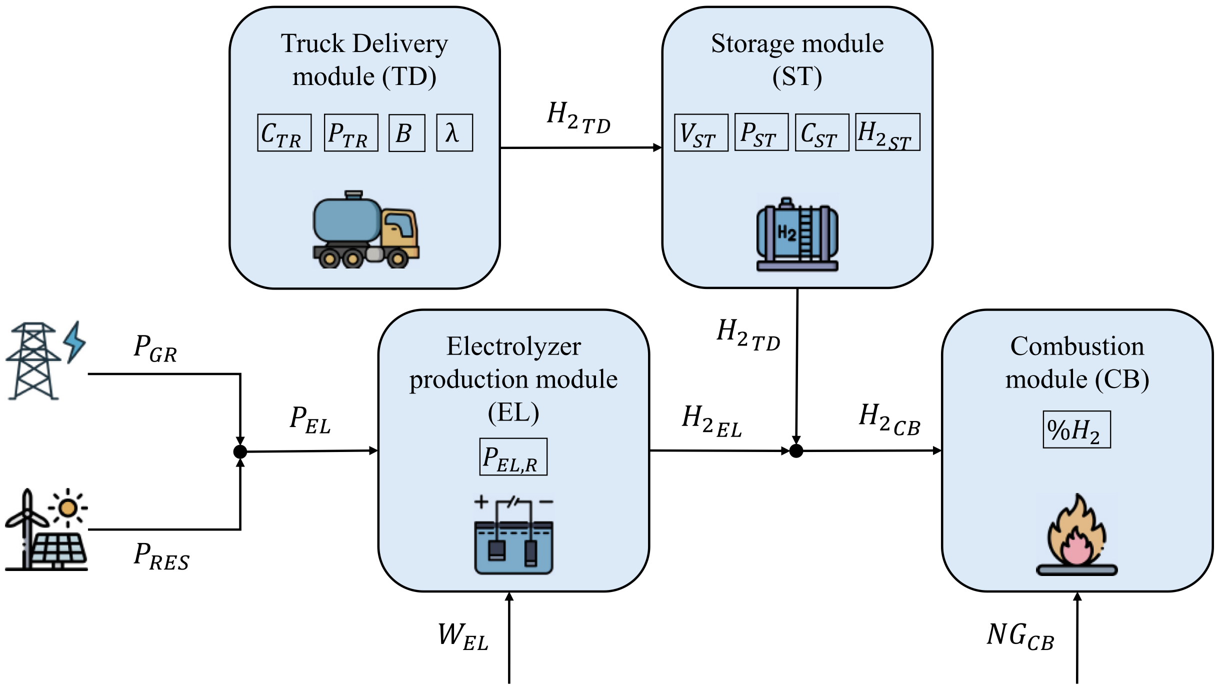

Fig. 2. Schematic representation of the system considering the main modules.

Table 2
Decision variables.

Notation	Description	Unit measure	Module
$\%H_2$	Percentage of hydrogen in fuel mix	–	CB
$P_{EL,R}$	Rated power of the electrolyzer	MW	EL
C_{TR}	Hydrogen capacity of truck	Nm^3	TD
P_{TR}	Hydrogen delivery pressure	bar	TD
P_{ST}	Target storage pressure	bar	ST
V_{ST}	Volume of the storage tank	m^3	ST

Table 3
Model outputs.

Notation	Description	Unit measure	Module
H_{2CB}	Average hourly hydrogen consumption	Nm^3/h	CB
NG_{CB}	Average hourly natural gas consumption	Nm^3/h	CB
$H_{2EL,N}$	Nominal hourly hydrogen production	Nm^3/h	EL
H_{2EL}	Average hourly hydrogen production	Nm^3/h	EL
P_{EL}	Average energy consumption	kW	EL
P_{GR}	Average electricity from grid	kW	EL
P_{RES}	Average electricity from renewables	kW	EL
W_{EL}	Average water consumption electrolyzer	L/h	EL
H_{2TD}	Average hourly hydrogen delivered	Nm^3/h	TD
B	Maximum number trucks unloading	truck	TD
λ	Truck arrival rate	truck/h	TD
$C_{ST,R}$	Required storage capacity tank	Nm^3	ST
C_{ST}	Storage capacity tank	Nm^3	ST
H_{2ST}	Average hydrogen level tank	Nm^3	ST

Depending on the hydrogen demand, the average hydrogen production flow from the electrolyzer may differ from its nominal performance. The actual hourly hydrogen production from the electrolyzer can be determined as in (2).

$$H_{2EL} = \begin{cases} H_{2EL,N} \text{ if } H_{2EL,N} \leq H_{2CB} \\ H_{2CB} \text{ if } H_{2EL,N} > H_{2CB} \end{cases} \tag{2}$$

The process of water electrolysis involves using electricity to split water molecules, resulting in the production of hydrogen. Consequently, electricity and water serve as the primary inputs for this process. The requirements for both inputs depend on the actual hourly hydrogen production rate and are estimated in (3) and (4), respectively.

$$P_{EL} = \frac{H_{2EL} \cdot LHV_{H_2}}{\eta_{EL}} \tag{3}$$

Table 4
Model parameters.

Notation	Description	Unit measure	Module	Value	Reference
NG_D	Current average hourly natural gas demand	Nm^3/h	CB	Confidential	Case study
LHV_{NG}	Lower Heating Value natural gas	kWh/Nm^3	CB	10.169	[28]
LHV_{H_2}	Lower Heating Value hydrogen	kWh/Nm^3	CB	2.994	[28]
η_{EL}	Electrolyzer nominal efficiency	–	EL	0.6	[29]
w_Q	Unitary water consumption electrolyzer	L/Nm^3	EL	10.7	[30]
u	Truck unloading time	h	TD	1	[31,32]
n_D	Receiving docks	–	TD	5	Assumption
MFP_{ST}	Minimum filling percentage tank	–	ST	0.2	Assumption
P_A	Atmospheric pressure	bar	ST	1.0087	Case study
ρ_{H_2}	Hydrogen density (standard conditions)	kg/Nm^3	All	0.0898	[33]
d	Discount rate	/year	All	0.04	[15,34]
N	System lifetime	years	All	20	[15,35]
T	Hours in a year	h/year	All	8760	–

$$W_{EL} = H_{2EL} \cdot w_Q \tag{4}$$

Lastly, equation (5) is included to balance the input electricity flow.

$$P_{EL} = P_{GR} + P_{RES} \tag{5}$$

4.1.2. Truck delivery module

Compressed hydrogen delivered by truck represents another option for hydrogen supply. The average hourly hydrogen required to be externally supplied by trucks is estimated as in (6).

$$H_{2TD} = H_{2CB} - H_{2EL} \tag{6}$$

Consequently, equation (7) allows estimating the required truck arrival rate.

$$\lambda = \frac{1}{H_{2TD}/C_{TR}} \tag{7}$$

To ensure that the number of trucks unloading hydrogen at the same time does not exceed the facility's capacity in terms of receiving docks (with 99 % probability), the arrival rate must satisfy constraints (8) and (9), where (8) is derived directly from the Poisson distribution.

$$1 - \left(\sum_{b=0}^{B} \frac{(\lambda u)^b \cdot \exp(-\lambda u)}{b!} \right) \leq 0.01 \tag{8}$$

$$B \leq n_D \tag{9}$$

4.1.3. Storage module

When relying on the external supply, a storage tank must also be included in the system as it is required to accommodate the hydrogen exceeding the furnace's immediate requirements. The required storage capacity must cover the difference between the maximum truck unloading rate (based on the highest number of trucks unloading) and the maximum hydrogen demand rate (when the electrolyzer is inactive), and a minimum filling percentage is considered, as shown in (10).

$$C_{ST,R} = \frac{\left(B \cdot \frac{C_{TR}}{u} - H_{2CB} \right) \cdot u}{(1 - MFP_{ST})} \tag{10}$$

The actual storage tank capacity, which is a function of the target storage pressure and volume of the tank, according to (11), must verify (12).

$$C_{ST} = \frac{V_{ST} \cdot P_{ST}}{P_A} \tag{11}$$

$$C_{ST} \geq C_{ST,R} \tag{12}$$

Based on the actual capacity of the storage tank, the average level of hydrogen contained inside is estimated as in (13).

$$H_{2ST} = MFP_{ST} \cdot C_{ST} + \frac{\left(B \cdot \frac{C_{TR}}{u} - H_{2CB} \right) \cdot u}{2} \tag{13}$$

4.1.4. Combustion module

The combustion process occurs within the furnace to reach the high temperatures necessary for melting raw materials. In many industrial furnaces, natural gas is currently the only fuel used for combustion. Hydrogen can be used at this stage to either partially or completely replace the natural gas flow.

The required average hourly hydrogen supply to the furnace to meet the combustion requirements can be estimated by accounting for the different *LHVs* of the fuels, as shown in (14).

$$H_{2CB} = \%H_2 \cdot NG_D \cdot \frac{LHV_{NG}}{LHV_{H_2}} \tag{14}$$

Natural gas may still be required in the combustion process, depending on the percentage of fuel replaced by hydrogen. The average hourly natural gas supply to the furnace can be estimated as in (15).

$$NG_{CB} = (1 - \%H_2) \cdot NG_D \tag{15}$$

The flows in the reference scenario are determined by setting the hydrogen percentage in the fuel mix $\%H_2$ in (14) and (15) equal to 0.

4.2. Performance indicators

4.2.1. Cost performance indicators

Following common approaches in the literature [15], the cost performance indicators adopted are the levelized cost of hydrogen (LCOH) and the levelized cost of energy (LCOE). The evaluation of the investment cost (IC) and the annual operating cost (OC) for each specific module is provided in the Supplementary Material.

The LCOH, measured in €/kg, represents the average cost per unit of hydrogen in the system over its lifetime. It is estimated as in (16).

$$LCOH = \frac{IC_{EL} + IC_{TD} + IC_{ST} + \sum_{n=1}^{N} \frac{OC_{EL} + OC_{TD} + OC_{ST}}{(1+d)^n}}{\sum_{n=1}^{N} \frac{H_{2CB} \cdot \rho_{H_2} \cdot T}{(1+d)^n}} \tag{16}$$

The LCOE, measured in €/kWh, refers to the average cost per unit of energy demanded over the system's lifetime. It can be generally estimated starting from the overall system net present cost (NPC), which is computed as in (17).

$$NPC = IC_{EL} + IC_{TD} + IC_{ST} + \sum_{n=1}^{N} \frac{OC_{EL} + OC_{TD} + OC_{ST} + OC_{CB}}{(1+d)^n} \tag{17}$$

Based on (17), the LCOE is derived as in (18).

$$LCOE = \frac{NPC}{\sum_{n=1}^{N} \frac{(H_{2CB} \cdot LHV_{H_2} + NG_{CB} \cdot LHV_{NG}) \cdot T}{(1+d)^n}} \tag{18}$$

4.2.2. Inherent safety performance indicators

The Inherent Safety Key-Performance Indicators (IS-KPIs) [23] are introduced in the analysis, and they include the inherent Hazard Index (HI) and the Potential hazard Index (PI). These indicators require evaluating the Unit inherent Hazard Index (UHI) and the Unit Potential hazard Index (UPI) for each component k included in the system's modules, whose detailed estimation approach is provided in the Supplementary Material.

The HI, measured in m^2/year, quantifies the combination of the potential damage from loss of containment (LOC) events and their likelihood, and is estimated as in (19).

$$HI = \sum\nolimits_{k \in EL} UHI_k + \sum\nolimits_{k \in TD} UHI_k + \sum\nolimits_{k \in ST} UHI_k + \sum\nolimits_{k \in CB} UHI_k \tag{19}$$

The PI, measured in m^2, expresses the maximum potential damage and is estimated as in (20).

$$PI = \sum\nolimits_{k \in EL} UPI_k + \sum\nolimits_{k \in TD} UPI_k + \sum\nolimits_{k \in ST} UPI_k + \sum\nolimits_{k \in CB} UPI_k \tag{20}$$

4.2.3. Environmental performance indicators

The Global Warming Potential (GWP), measured in kg of carbon dioxide equivalents (kg CO_2e), quantifies the overall effect due to greenhouse gas emissions [11]. The total annual GWP and its annual percentage variation (GWP_V) between the reference scenario (AS-IS) and the hydrogen-based configurations (TO-BE) are introduced to assess the environmental performance of the system. These indicators are estimated as shown in (21) and (22).

$$GWP = GWP_{EL} + GWP_{TD} + GWP_{CB} \tag{21}$$

$$GWP_V = \frac{GWP_{TO-BE} - GWP_{AS-IS}}{GWP_{AS-IS}} \cdot 100 \tag{22}$$

The GWP assessment in this study does not account for emissions related to the manufacturing of system components or the potential climate impact of hydrogen leakages within the system [36]. Consequently, the storage module is assumed to have no contribution to the overall GWP. The specific evaluation of the GWP associated with each of the other modules is provided in the Supplementary Material. Notably, in the AS-IS scenario, the combustion module is the sole contributor to GWP.

Additionally, the annual water footprint (WF), measured in L/year, is estimated as shown in equation (23), reflecting the significance of water as a key input for electrolysis and its increasing global scarcity [37].

$$WF = W_{EL} \cdot T \tag{23}$$

5. Scenario analysis and case study

Scenario analysis is conducted by assigning different values to the model's decision variables to evaluate the performance of different hydrogen-based system configurations. Table 5 summarizes the initial values considered for the scenario analysis.

The values for each decision variable are mainly based on commercially available solutions, except for $\%H_2$, whose values are chosen by the authors.

Each value for the hydrogen delivery pressure occurs only with the corresponding value of truck capacity. As a result, Table 6 shows the available alternatives for the truck delivery (TD) option.

Additionally, some values for the target storage pressure and tank volume are excluded to comply with the physical model constraints, specifically (11) and (12), as many combinations do not meet the required storage capacity. Table 7 shows the available storage tank (ST) options, with those satisfying the constraints in at least one scenario highlighted in bold.

Based on the above considerations, 217 hydrogen-based system configurations were analyzed in addition to the reference scenario. In the remainder of the paper, the resulting decision variables (hydrogen percentage in the fuel mix, electrolyzer power rated, truck delivery alternative and storage tank alternative) are referred to as factors.

A reference case study is adopted for the rest of the analysis. It consists of a glass company located in France, which is currently fulfilling its electricity requirements using green electricity supplied by a nearby hydroelectric dam. As an alternative for electricity source, the company can utilize the French electrical grid, which is a relatively low-carbon option, comprising nuclear energy (64 %), hydropower (12 %), wind (10 %), and natural gas (6 %) [38].

6. Results and discussion

This section presents the study results, starting with an unconstrained analysis in Section 6.1, where all hydrogen-based configurations are evaluated simultaneously, initially including the reference scenario. In Section 6.2, constraints to reflect potential company requirements are introduced, and the results are discussed, in some cases complemented by a sensitivity analysis.

Table 5
Initial values used for the scenario analysis.

Decision Variable	Values	Unit of measure
$\%H_2$	0.25; 0.5; 0.75; 1	–
$P_{EL,R}$	0; 0.5; 1; 1.25; 2; 2.5; 3; 5	MW
C_{TR}	5088; 6179; 7204; 8172	Nm^3
P_{TR}	200; 250; 300; 350	bar
P_{ST}	35; 50; 70	bar
V_{ST}	50; 100; 200	m^3

Table 6
Available alternatives for truck delivery option.

Truck delivery (TD) alternative	P_{TR} [bar]	C_{TR} [Nm^3]
TD1	200	5088
TD2	250	6179
TD3	300	7204
TD4	350	8172

Table 7
Available alternatives for storage tank option.

Storage tank (ST) alternative	P_{ST} [bar]	V_{ST} [m^3]
ST1	35	50
ST2	35	100
ST3	**35**	**200**
ST4	50	50
ST5	50	100
ST6	**50**	**200**
ST7	70	50
ST8	**70**	**100**
ST9	**70**	**200**

6.1. Unconstrained analysis

The reference scenario minimizes costs and enhances safety performance. However, this approach does not contribute to meeting decarbonization targets. Table 8 summarizes the performance metrics, where LCOH is not included due to the absence of hydrogen in this scenario.

The figures below illustrate the impact of the previously defined factors on the main system performance (i.e., LCOH, HI, PI and GWP_V) across all hydrogen-based configurations. As illustrative examples, only two hydrogen percentage values in the fuel mix are displayed. The analysis is based on the reference assumptions that hydropower supplies the electrolyzer, and grey hydrogen, produced from fossil fuels through steam methane reforming (SMR), is the alternative external supply, reflecting its status as the most commercially available hydrogen type [39].

Fig. 3 presents the effect of the factors on the LCOH, represented on the y-axis. The y-axis is split into two plots to show the impact of the two hydrogen percentages in the fuel mix. The x-axis indicates the different levels of electrolyzer power rated, and it is further subdivided into the corresponding storage tank and truck delivery alternatives available. For instance, when selecting an electrolyzer with a rated power of 1.25 MW, all truck delivery alternatives (TD1, TD2, TD3, and TD4) are available to supply the additional hydrogen flow. However, the available storage tank options strictly depend on the specific truck delivery alternative since storage requirements are directly linked to truck capacity. For example, TD1 allows for all storage tank options (ST3, ST6, ST8, and ST9). In contrast, truck delivery options characterized by a higher truck capacity restrict the choice of storage tanks to those with larger storage capacities (ST6 and ST9). It is important to note that when the electrolyzer's rated power is sufficiently high to meet the hydrogen demand, truck delivery is no longer needed, eliminating the need for storage as well. These scenarios are represented by the green bars. The structure of the graph remains consistent in Figs. 4–6.

Fig. 3 shows that the truck delivery and storage tank options have a negligible effect on LCOH values. In contrast, the most significant

Table 8
System performance for baseline scenario, where fuel mix is only composed of natural gas.

LCOE	0.066 €/kWh
HI	0.011 m^2/year
PI	77 m^2
GWP	3,620,653 kg CO2e/year

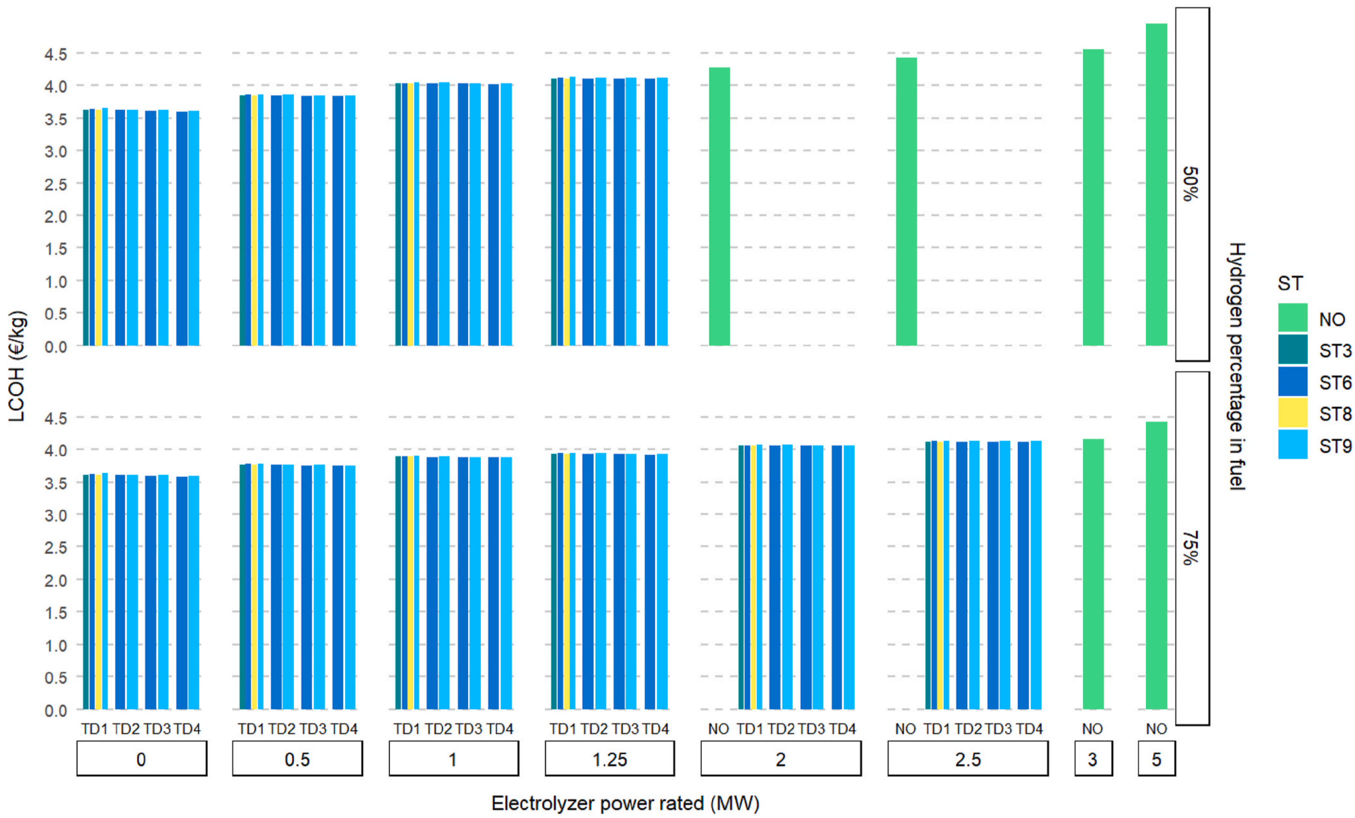

Fig. 3. Factors effect on LCOH.

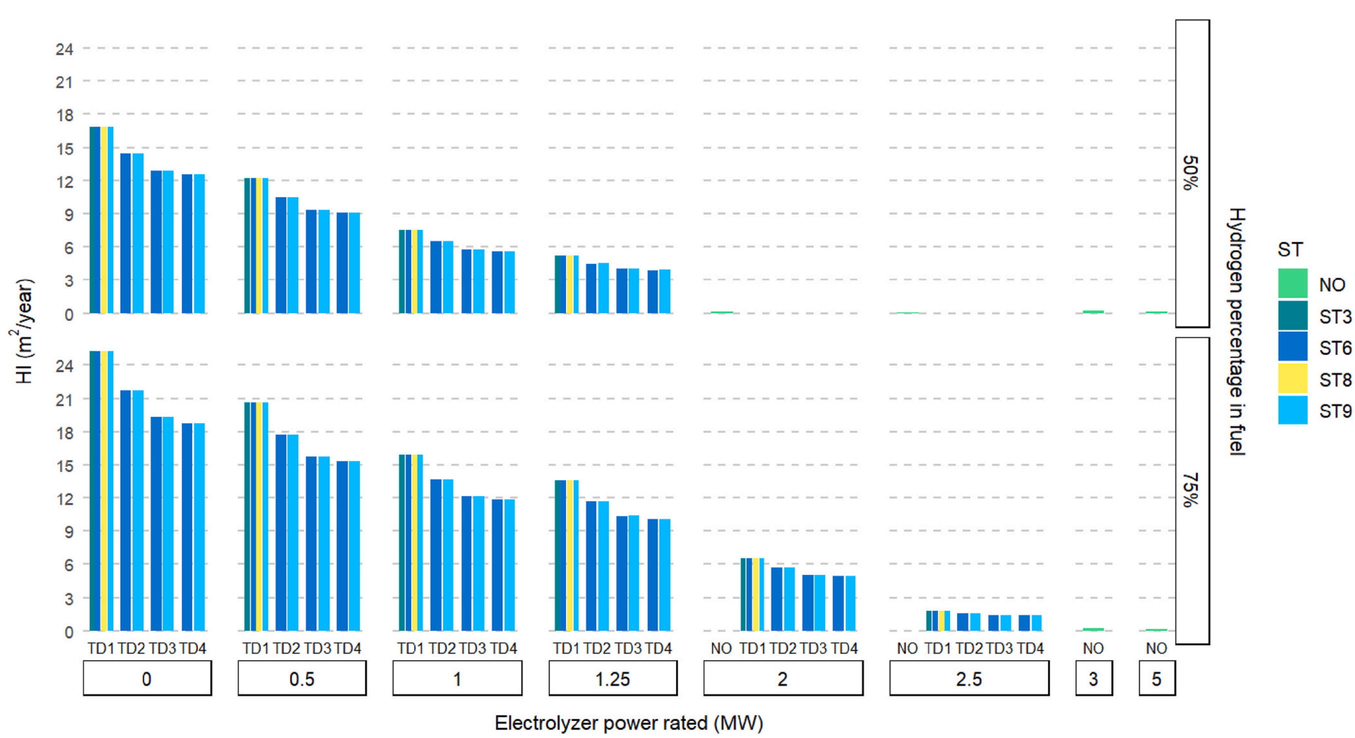

Fig. 4. Factors effect on HI.

impact on LCOH comes from the choice of electrolyzer capacity and the hydrogen percentage in the fuel mix. While LCOH increases with higher electrolyzer power rated, it decreases as the hydrogen percentage rises. This is because, under the given assumptions, on-site hydrogen production is more expensive than external supply and a higher hydrogen percentage in the fuel mix results in a greater dependence on externally supplied hydrogen for a specific electrolyzer capacity.

Similarly, Fig. 4 shows the effect of the factors on HI. Truck delivery

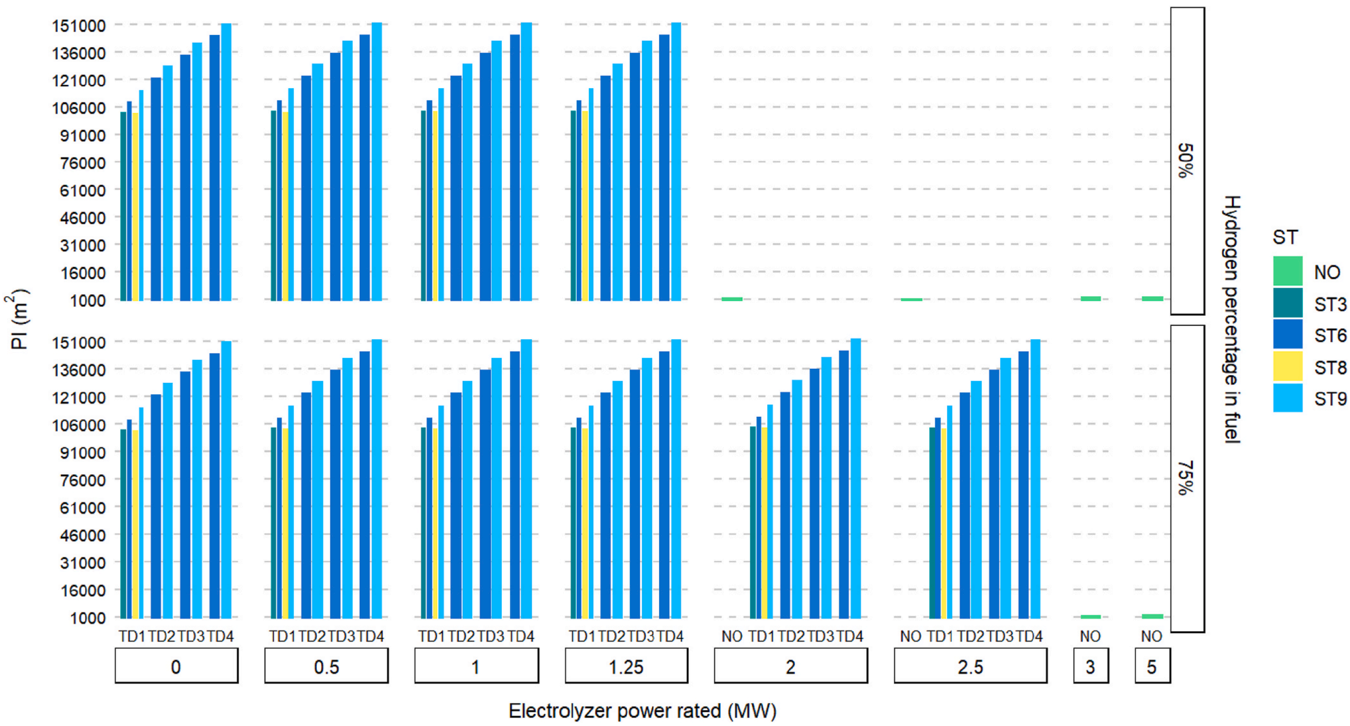

Fig. 5. Factors effect on PI.

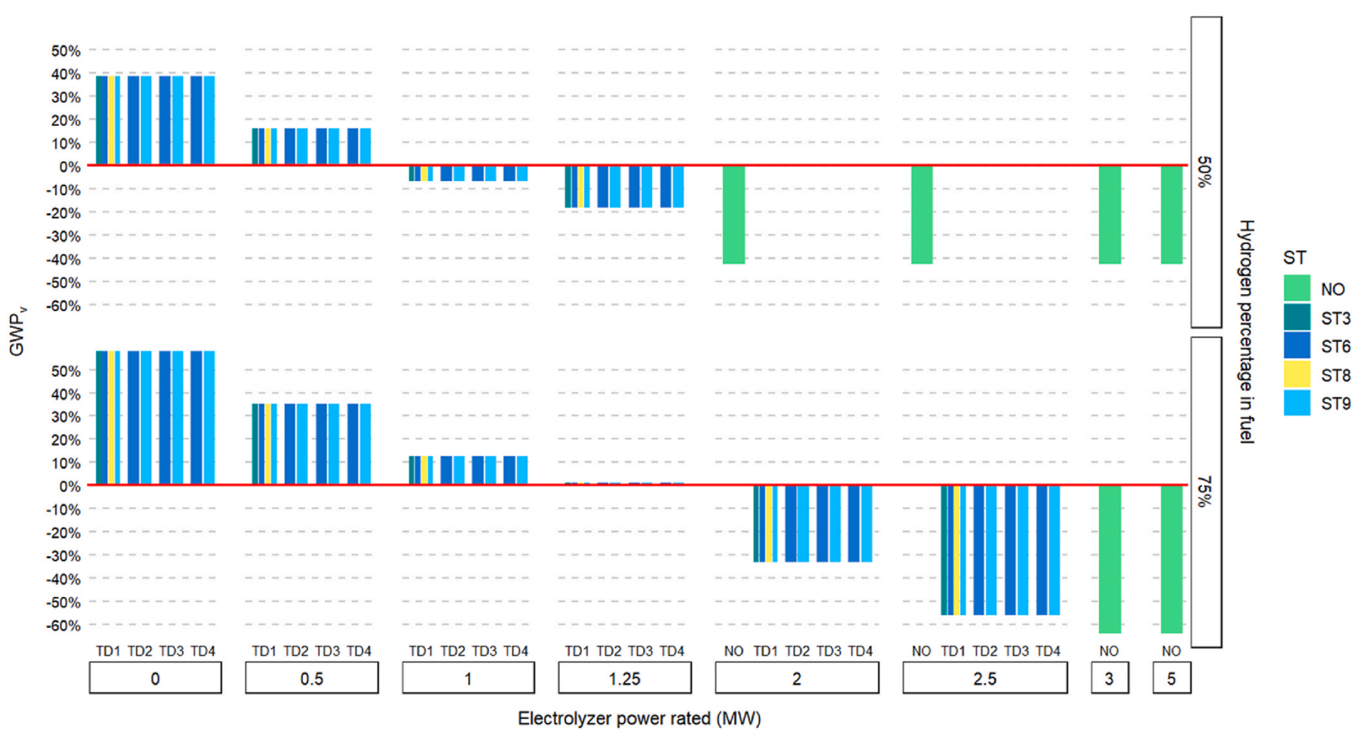

Fig. 6. Factors effect on GWP_V.

alternative and electrolyzer capacity are the most impactful. Keeping the external supply fixed, HI decreases as truck capacity increases. Selecting a lower-capacity truck delivery option, such as TD1, leads to higher truck arrival rates and more frequent use of the flexible hoses connecting the truck. As the hoses have the highest likelihood of LOC events, their increased usage significantly raises the HI. Likewise, increasing electrolyzer capacity reduces the HI by reducing reliance on external supply and truck hose usage. Different storage alternatives show minimal variation in HI.

Fig. 5 provides the results for the PI, which are entirely driven by truck delivery and storage alternatives. Specifically, PI increases with higher truck and storage capacities. A significant reduction in PI occurs only when the electrolyzer capacity is sufficient to cover the hydrogen demand, without requiring an external supply (green bars).

The different impact of each factor on the IS-KPIs stems from the nature of these indicators. The PI captures the worst-case consequences of LOC events. The truck and the storage tank have the most significant impact on PI, and a change in their capacity significantly affects the performance, as shown in Fig. 5. In contrast, the HI accounts also for the likelihood of LOC events. In this case, the usage of truck hoses dominates the results because their probability of having LOC events is much higher than all the other components.

Combining the effects on PI and HI suggests that high-capacity storage tanks should be excluded. The impact on HI is negligible, while Fig. 5 shows that smaller storage capacities decrease the PI. When only ST6 and ST9 are possible solutions, ST9 is preferred. However, when all storage options are available, ST3 and ST8 offer equivalent performance.

Unfortunately, the different trends of the two indicators do not allow identifying an overall safest solution, except for configurations relying solely on on-site production, which are also the most expensive. A possible way forward is to prioritize solutions minimizing HI, while implementing strategies to mitigate higher PI values, such as ensuring sufficient safety distances around the delivery area. Selecting truck delivery options with lower arrival rates also reduces exposure to risks associated with external supply disruptions (e.g., delivery delays or operational accidents). Additionally, reduced use of truck hoses leads to lower maintenance costs for these components once the system is operational.

It is worth emphasizing that the assessment of the IS-KPIs indicators relies on several assumptions, reflecting the novelty of applying this approach to on-site hydrogen supply systems design. Due to the strongly context-dependent nature of the evaluation, the results should be used in relative terms, namely for the comparison of alternative configurations that serve the same functional objective (i.e., supplying hydrogen to industrial furnaces). Thus, this study evaluates different hydrogen supply configurations and benchmarks them against the reference scenario, which relies only on natural gas combustion. A comparative perspective can also be drawn with previous studies that have applied IS-KPIs within the hydrogen domain; however, system-specific differences limit the possibility of a direct one-to-one evaluation. For this comparative purpose, Table D.1 in the Supplementary Material presents detailed results associated with a representative configuration analyzed in this study. Schiaroli et al. [27] assessed storage solutions for buses and reported a UPI of approximately 2.5×10^3 m^2 for a fuel tank of 7.8 kg at 350 bar. Their result is at least one order of magnitude lower than the representative truck and storage configurations from the present study, reflecting the significantly higher fuel amounts involved in the current analysis (555 kg at 250 bar and 590 kg at 50 bar, respectively). Conversely, Schiaroli et al. [27] estimated a higher UHI (12 m^2/year), attributable to the higher credit factors assigned to LOCs for urban mobility tanks compared to those applied to the LOCs for stationary storage vessels and pressured transport equipment in the present study. Landucci et al. [24] assessed the inherent safety of the hydrogen value chain up to vehicle applications; however, the absence of operational details for individual components constrains the possibility of direct comparison. Landucci et al. [26] investigated medium-scale storage (500 kg at 250 bar), which is dimensionally comparable to the representative truck evaluated in the current study. Indeed, the authors obtained a value for the UPI (1.1×10^5 m^2) with an order of magnitude comparable to the results for the representative truck in the present study. Finally, Tugnoli et al. [23] examined large-scale grey hydrogen production via SMR, reporting substantially higher IS-KPI values. Nevertheless, a direct comparison is not feasible due to differences in both production technology and capacity scale.

As concerns the environmental impact, Fig. 6 shows how the different factors affect GWP_V, which represents the annual percentage reduction in equivalent CO_2 emissions. Unlike previous plots, both positive and negative performance values appear, indicating that some configurations result in worse performance compared to current emission levels. Under the assumptions considered, the external hydrogen supply has a higher environmental impact than the on-site production. While increasing the hydrogen percentage in the fuel mix reduces direct emissions from combustion, overall emissions tend to rise when all other factors remain constant. This occurs because a larger share of hydrogen is sourced externally, and the reduction in direct emissions is insufficient to offset the higher environmental impact of the external grey hydrogen supply. As a result, the GWP_V trend mirrors that of the HI, with better performance observed for higher electrolyzer capacities.

Additionally, to provide a more comprehensive environmental assessment, the annual WF is evaluated across the different hydrogen-based configurations. As this indicator is specific to the electrolysis process, the results are solely influenced by the electrolyzer capacity. Water consumption is directly proportional to the amount of hydrogen produced on-site, reaching a maximum WF of approximately 6 million L/year under the scenario of full hydrogen substitution with complete on-site production.

Overall, increasing the electrolyzer size improves safety performance and reduces overall emissions, regardless of the hydrogen share in the fuel mix, but at the expense of higher costs and water consumption. None of the evaluated configurations offers simultaneous improvements across all performance dimensions. Therefore, the most suitable option depends on the specific context and application requirements.

6.2. Constrained analysis

The following subsection examines various cases, each reflecting distinct internal and external constraints a company may face, and provides key considerations for hydrogen-based system design. Based on the above discussion on the IS-KPIs, the analysis focuses solely on the truck delivery option TD4 and the storage alternatives ST8 (when available) or ST6. Section 6.2.1 investigates the impact of limiting the hydrogen share in the fuel mix, a constraint commonly examined in similar studies [26,11,34]. This is followed by an analysis of the effect of constraining emissions reduction targets in Section 6.2.2 [40]. Section 6.2.3 considers limitations in the available capacity of renewable energy technologies, a scenario that, to our knowledge, has not been fully explored in the literature, as most studies focus on optimal sizing rather than actual availability. Lastly, Sections 6.2.4 and 6.2.5 provide more qualitative insights into the effects of limiting on-site hydrogen production and ensuring minimum safety performance, a novel analysis for hydrogen introduction at the industrial plant level. The analyses are supported by sensitivity analyses on key factors influencing design outcomes. In line with established literature, the effects of electricity price, electricity carbon intensity, and hydrogen purchasing costs are investigated [9,14,36]. Additionally, this study extends the analysis by exploring the type of hydrogen that can be externally delivered (green, grey or blue), considering both cost and environmental implications, an aspect that has received limited attention in previous studies.

6.2.1. Effect of constraints on hydrogen percentage in the fuel mix on hydrogen-based system design

The first relevant case to investigate is a specific required percentage of hydrogen in the fuel mix. This constraint may arise due to different reasons, such as customers' sustainability requirements, which demand a certain percentage of hydrogen in producing the final delivered products. Another reason could be limiting the percentage of hydrogen in the fuel mix to optimize melting conditions. Indeed, preliminary research has shown that the hydrogen content in the fuel affects foam formation, which in turn can impact the quality of the final product [37,38]. Lastly, future government incentives could be introduced to promote specific hydrogen shares in heating applications. Fig. 7 shows the behavior of LCOH, HI, and GWP_V (indicated by the labels) across different hydrogen percentages in the fuel mix.

The trade-off between cost and safety performance is evident,

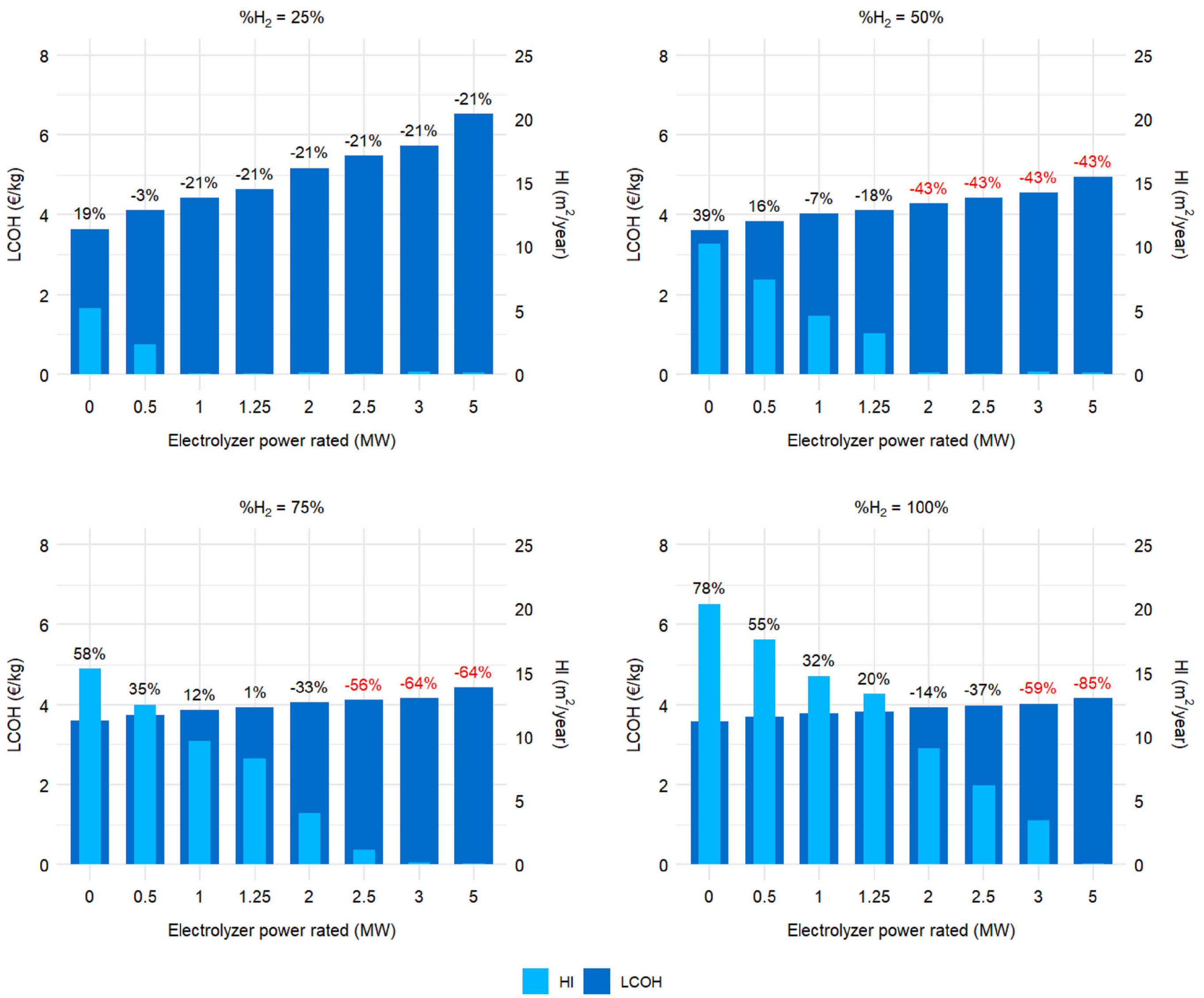

Fig. 7. LCOH, HI and GWP_V behavior for different $\%H_2$. The red labels refer to meeting a specific GWP_V target of −40 %. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

underscoring the challenge of balancing economic and safety objectives, regardless of the hydrogen share. Under the reference assumptions, fully relying on an external hydrogen supply minimizes costs but results in low safety performance. In contrast, increasing on-site hydrogen production enhances safety performance, but raises costs. Intermediate solutions for each specific case can be identified. Considering a fuel mix containing 100 % hydrogen, an intermediate solution could be using an electrolyzer with a 2 MW capacity, which allows covering around 56 % of the average hydrogen required. This solution has an LCOH of around 3.93 €/kg and an HI equal to 11.14 m^2/year. Compared to current operations, this solution eliminates direct combustion emissions for the manufacturer but only reduces overall emissions by 14 %. Additionally, it increases the LCOE from 0.07 €/kWh to 0.14 €/kWh compared to current levels.

It is important to note that the economic outcomes, and consequently the scenarios yielding intermediate LCOH and HI values, depend highly on electricity cost and the price of externally supplied hydrogen. Fig. 8 summarizes a sensitivity analysis of these external parameters for a complete hydrogen transition (100 % hydrogen in the fuel mix). Fig. 8a illustrates how LCOH varies with electricity prices (represented by the error plot), which are strongly influenced by the plant's location and geopolitical factors. The reference price for hydropower is set at 0.06 €/kWh, with a ±0.04 €/kWh range based on historical data from major hydropower-producing countries.

Fig. 8a shows that electricity price variations significantly impact hydrogen costs, especially for larger electrolyzers. For a 3 MW electrolyzer, LCOH can range from 2.15 to 5.89 €/kg, more than doubling in cost. Moreover, different electricity prices can completely shift the optimal source of hydrogen. At an electricity price of 0.1 €/kWh (upper extreme of the black lines), increasing the electrolyzer capacity from 1.25 MW to 2 MW results in a 12 % increase in LCOH. Conversely, at a lower hydropower price of 0.02 €/kWh (lower extreme of the black lines), investing in the larger electrolyzer results in a 12 % reduction in LCOH while also achieving a 32 % reduction in HI.

Fig. 8b analyzes the impact of external hydrogen price variations. While the reference price was set to 3.5 €/kg (approximately 0.3 €/Nm^3) [41], this analysis considers a range between 0.7 and 5.3 €/kg (approximately between 0.06 and 0.48 €/Nm^3) [39]. Unlike electricity prices, LCOH variation decreases with larger electrolyzer due to reduced reliance on external supply. Similar opposite patterns emerge when considering very different external hydrogen prices. When an external hydrogen supply price of 5.3€/kg is considered (upper extreme of the black lines), reducing dependence on external hydrogen and expanding electrolyzer capacity from 1.25 to 2 MW results in a 3 % reduction in

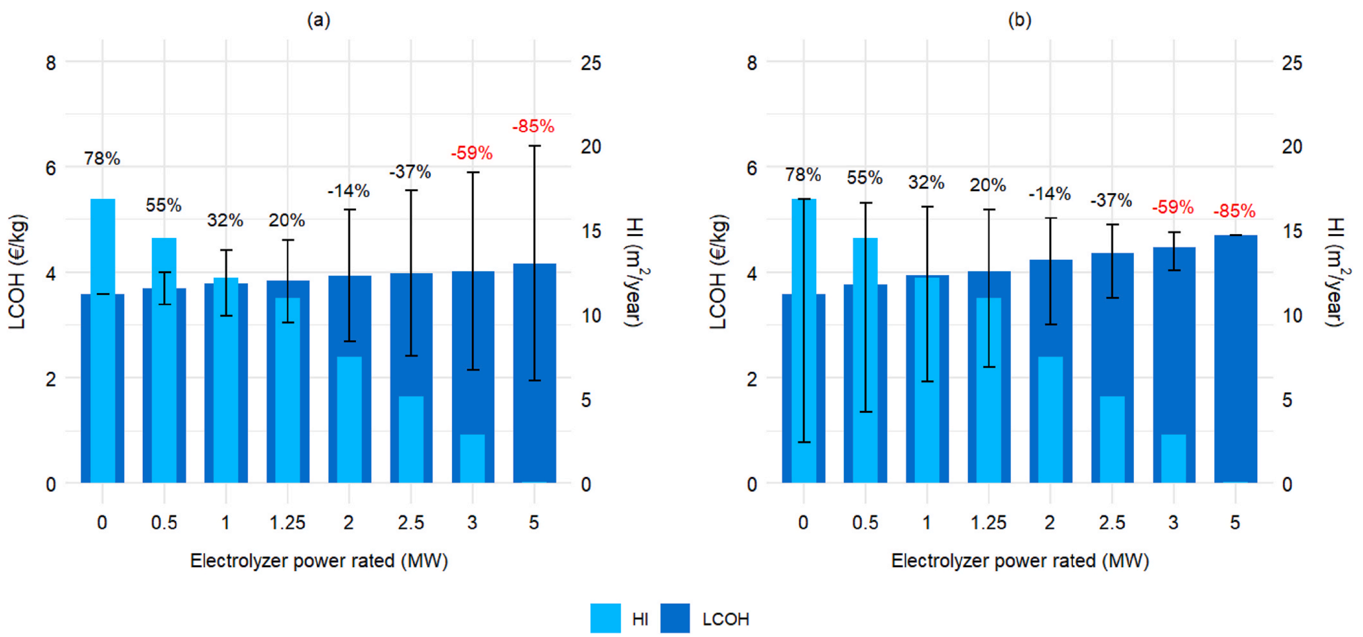

Fig. 8. Effect of variations in hydropower (a) and external hydrogen supply (b) prices on LCOH. The red labels refer to meeting a specific GWP_V target of −40 %. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

LCOH, along with significantly improved safety performance. On the contrary, when considering an external hydrogen price of 0.7 €/kg (lower extreme of the black lines), increasing internal capacity leads to a significant rise in LCOH, up to 37 % in the same scenario. It can also be noted that smaller electrolyzer capacities expose companies more to external hydrogen price fluctuations. Therefore, when external hydrogen costs are highly uncertain, maintaining a higher on-site capacity can lead to better control of hydrogen costs and reduce volatility in final product prices. The opposite is valid when electricity prices exhibit high fluctuations; relying more on external supply may provide greater hydrogen cost stability. Hence, a thorough market analysis considering the country's peculiarities should be conducted before making design decisions.

6.2.2. Effect of constraints on equivalent CO_2 percentage reduction on hydrogen-based system design

Another important case involves meeting specific equivalent CO_2 reduction targets, which may be required to comply with regulatory standards or to meet sustainability goals. As shown in Fig. 7, if a minimum 40 % reduction is required (red labels), an electrolyzer capacity of at least 2 MW is necessary for a hydrogen share of 50 % in the fuel, while a capacity of at least 2.5 MW is needed for a 75 % hydrogen percentage and a 3 MW electrolyzer for complete hydrogen-based combustion. In other words, nearly all hydrogen must be produced on-site due to the high environmental impact of the external supply (grey hydrogen). Specifically, for a 50 % hydrogen share, the entire production must come from on-site electrolysis. For a 75 % hydrogen share, at least around 90 % must be produced on-site, while for 100 % hydrogen, around 85 % on-site production is sufficient to meet the target. This suggests that higher hydrogen shares allow for a limited external supply without compromising the emissions reduction goal. Under the given assumptions, achieving high emissions reduction targets, such as 100 % elimination of direct emissions and approximately 85 % overall emissions reduction, is only possible through complete hydrogen transition and full on-site production.

The electricity source and the type of externally supplied hydrogen are critical when designing a hydrogen-based system to meet a specific emissions percentage reduction target. Fig. 9 illustrates a scenario where renewable energy sources are unavailable, and the entire electricity demand is covered using the national grid. An average emission factor for electricity consumption is estimated at 0.061 kg CO_2e/kWh [42], significantly higher than the 0.017 kg CO_2e/kWh [43] associated with hydropower. In this case, only a full hydrogen transition with complete on-site production meets the same target, but the reduction achieved is nearly halved compared to the previously described case.

It is important to note that the choice of electricity source also affects electricity pricing, which in turn significantly impacts LCOH, particularly for larger electrolyzer capacities, as previously highlighted. The reference solution with full transition and on-site production is characterized by a 76 % increase in hydrogen cost (from 4.16 to 8.29 €/kg). In this specific context, investing in electrolyzer capacity while relying on the national grid might not be a favourable decarbonization option, as it neither enables achieving high emissions reduction targets nor ensures cost-effective hydrogen production.

At the same time, the type of externally supplied hydrogen plays a similarly crucial role in shaping the environmental performance of the analyzed scenarios. To illustrate this impact, blue hydrogen, a widely referenced hydrogen type in the literature [44], is considered alongside green hydrogen, given the different environmental impacts of their production processes compared to grey hydrogen. For reference, the emission factor for grey hydrogen production is set to 11 kg CO_2e/kg H_2 (approximately 0.99 kg CO_2e/Nm^3) [45]. Emissions from green hydrogen production can vary greatly depending on the renewable source used to power the water electrolysis process. Some estimated emission factors are 2.4 kg CO_2e/kg H_2 for solar, 0.68 and 0.63 kg CO_2e/kg H_2 for wind, and 0.77 kg CO_2e/kg H_2 for hydropower [46]. An average value of 1.1 kg CO_2e/kg H_2 (equivalent to 0.099 kg CO_2e/Nm^3) has been considered, aligning with the results for the on-site production in our model. Blue hydrogen, produced by steam methane reforming (SMR) like grey hydrogen but with an additional carbon capture and storage (CCS) process, reduces the emission factor to about half that of grey hydrogen [45]. Therefore, an emission factor of 5.5 kg CO_2e/kg H_2 (approximately 0.49 kg CO_2e/Nm^3) is assumed. Fig. 10 summarizes the results for different hydrogen types, each highlighted in its corresponding color classification, under the reference assumption of hydropower-based on-site electrolysis. The extent of overall emissions reduction varies depending on the hydrogen type, with significant reductions achievable even when outsourcing, despite

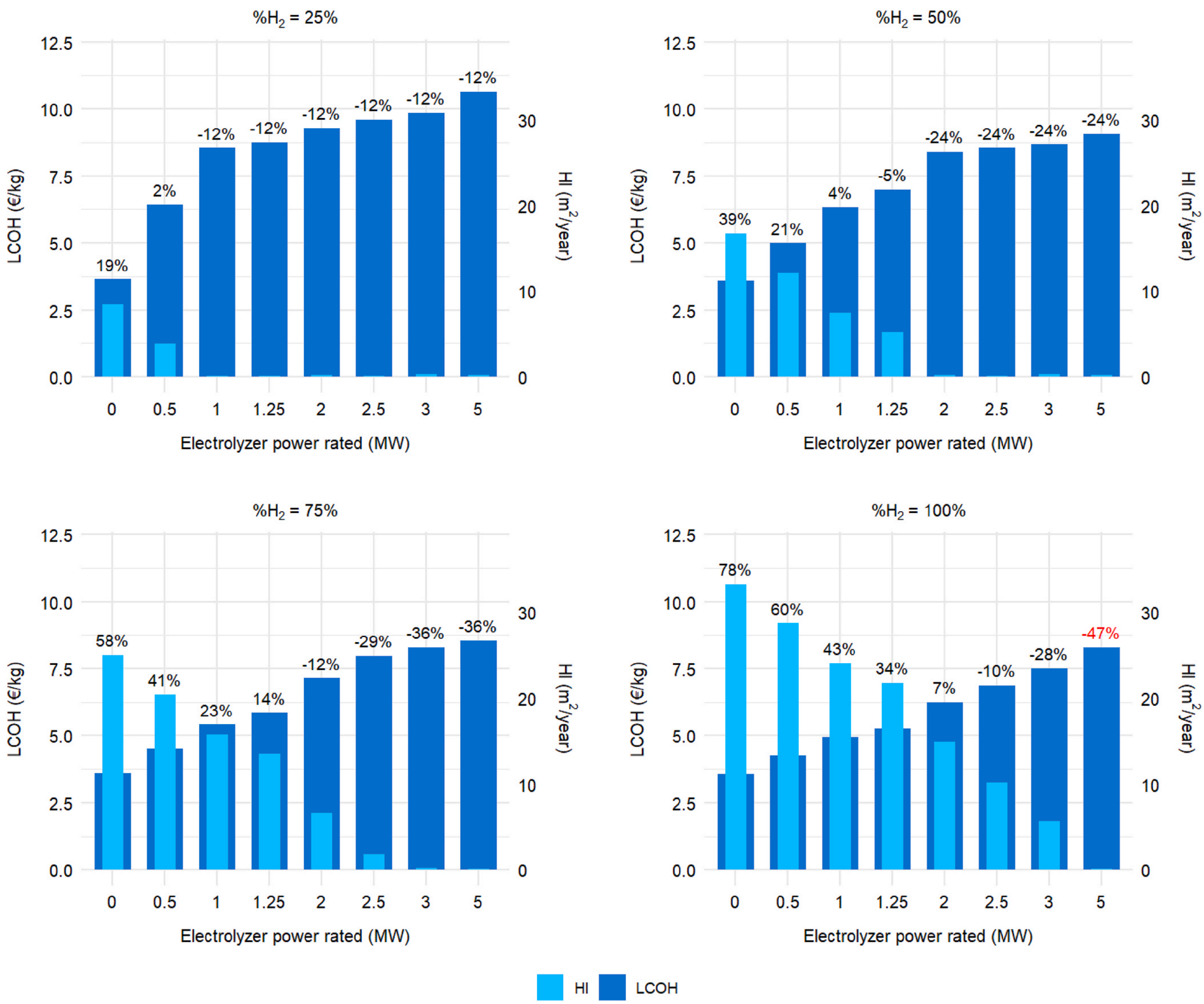

Fig. 9. Effect of change of electricity source on system performance for different %H_2. The red labels refer to meeting a specific GWP_V target of −40 %. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

transportation-related emissions. For instance, in a full hydrogen transition scenario with an internal electrolyzer capacity of 1 MW, where more than 70 % of hydrogen production is being outsourced, a GWP_V of almost 30 % is still achievable if a blue hydrogen external supply is available. This effect is even more pronounced when relying on an external supply of green hydrogen, where GWP reductions are observed across all system configurations.

Similarly to what is highlighted for electricity sources, the choice of externally supplied hydrogen indirectly affects economic performance due to variations in production costs. While the average grey hydrogen production cost in Europe is estimated to be 3.5 €/kg (approximately 0.3 €/Nm^3), blue and green hydrogen production costs are estimated at 4.41 and 6.61 €/kg, respectively (corresponding to around 0.4 and 0.6 €/Nm^3) [41]. When an external supply of blue hydrogen is available, it can be a preferable option over grey hydrogen, as the environmental benefits outweigh the differences in production costs. For instance, in the previously mentioned full hydrogen transition scenario with a 1 MW electrolyzer, meeting the additional hydrogen demand with blue hydrogen instead of grey hydrogen can lead to an almost 200 % improvement in emissions reduction, while LCOH increases by only 17 %. Notably, on-site production becomes cost-effective even at the reference electricity price when compared to an external supply of green hydrogen. This trend is evident in the decreasing green bars for increasing electrolyzer capacities when a full hydrogen transition is considered. The cost-effectiveness of the on-site production in this scenario is likely driven by the lower electricity costs associated with hydropower compared to other renewable sources, as well as the economies of scale linked to electrolyzer capacity.

6.2.3. *Effect of constraints on renewable energy availability on hydrogen-based system design*

Another case analyzed examines scenarios where the company faces constraints on renewable energy availability. This situation may arise when a company has already installed local renewable energy infrastructure but encounters limitations in expanding its capacity. This case is particularly relevant for glass manufacturers, who may have already implemented renewable energy technologies to supply green electricity for electrical boosting in furnaces. Fig. 11 shows the results for a reference case in which only 1 MWh of electricity is available from hydropower while the national electrical grid meets any additional demand. Depending on the specific context, partial reliance on the grid may be more or less advantageous for covering additional electricity needs. Under the reference assumptions and case study, using a lower share of hydrogen in the fuel mix may be preferable rather than striving for

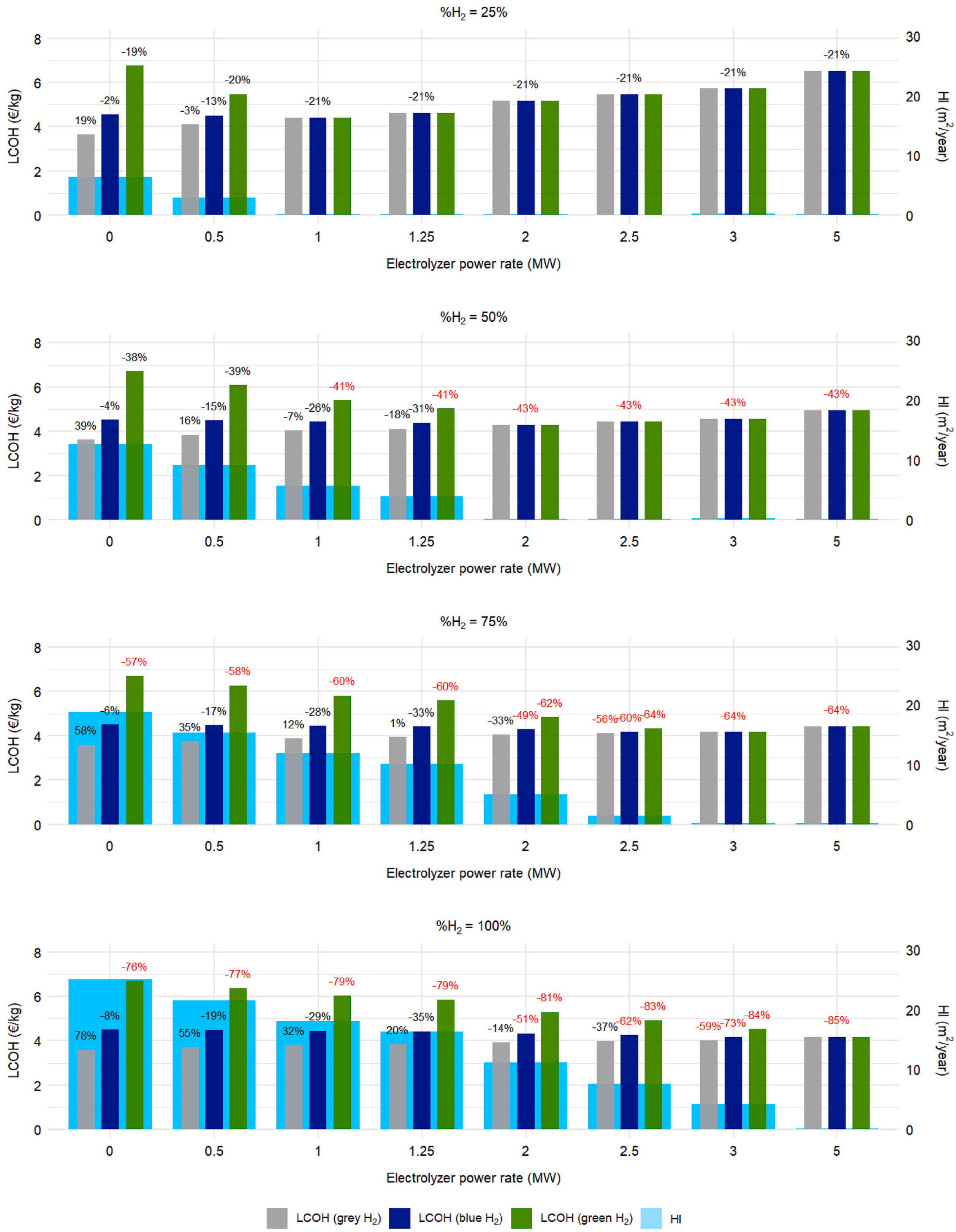

Fig. 10. Effect of external hydrogen supply type on system performance for different %H$_2$. The red labels refer to meeting a specific GWP$_V$ target of −40 %. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

higher percentages while relying on grid electricity. For instance, using a 1 MW electrolyzer with a hydrogen share of 25 % yields comparable environmental benefits to investing in a 2 MW electrolyzer and increasing the hydrogen share to 75 %. Both configurations achieve an overall GWP percentage reduction of approximately 20 %, although their impact on direct CO_2 emissions reduction differs. Moreover, the LCOH for the case with a larger electrolyzer increases by 27 %, and the HI rises by 63 % due to its partial dependence on an external supply. As

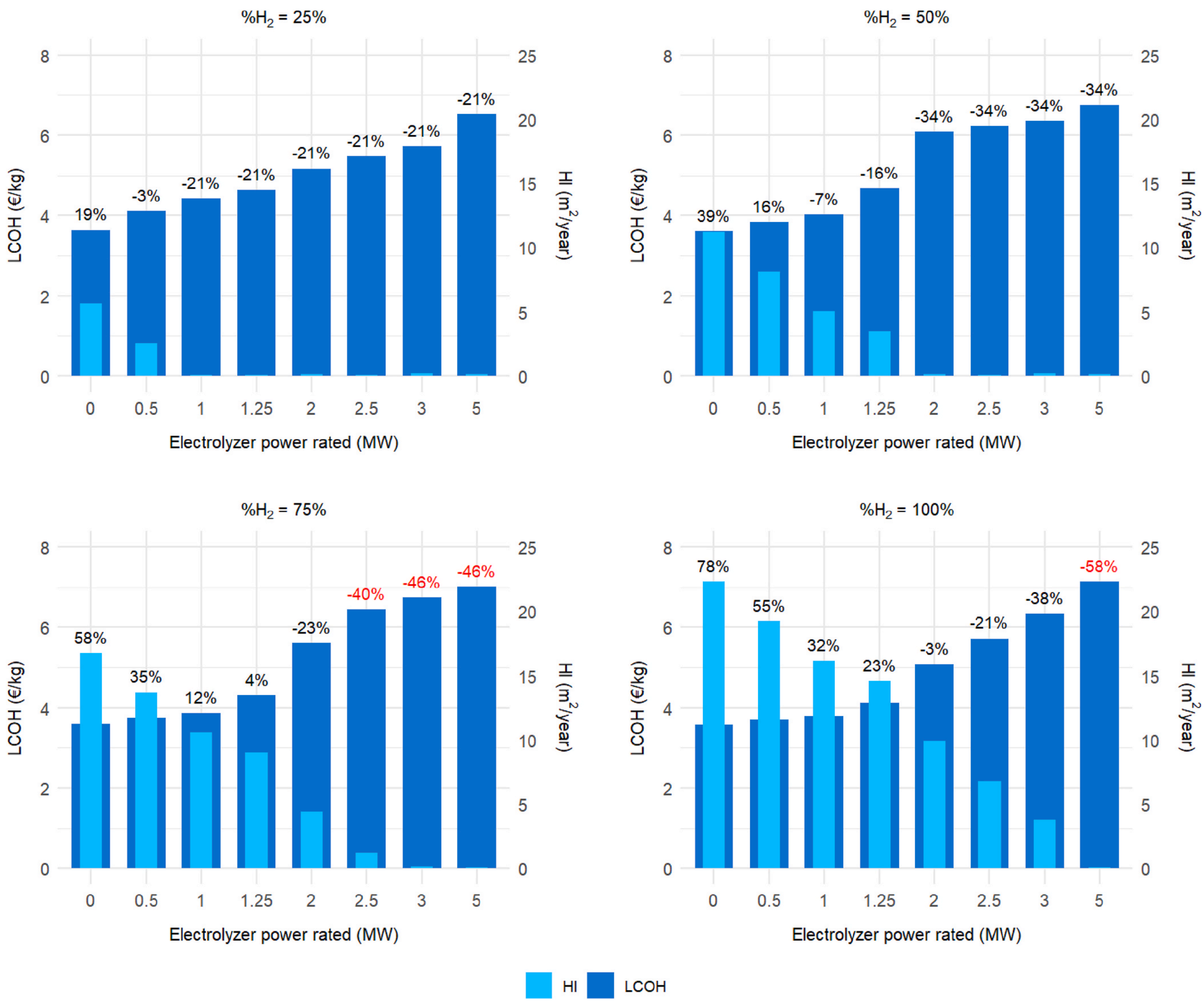

Fig. 11. Effect of limited renewable energy availability on LCOH, HI and GWP_V for different $\%H_2$. The red labels refer to meeting a specific GWP_V target of −40 %. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

previously discussed, these results are context-specific and highly sensitive to factors such as the emission intensity and cost of electricity sources, as well as the type of external hydrogen supply available.

6.2.4. Effect of constraints on on-site hydrogen production on hydrogen-based system design

Additional constraints may come from the company aiming to produce a specific share of its target hydrogen amount on-site. This may be driven by the need to maintain direct control over part of the hydrogen supply or as part of a broader strategy to outsource part of the demand, thereby enhancing operational flexibility. In such a case, the choice of the electrolyzer is straightforward, as its capacity directly determines the portion of hydrogen produced on-site. Consequently, the amount of hydrogen sourced externally is also well-defined. If the type of external supply remains variable, blue hydrogen represents an effective option to compensate for reduced on-site production. As depicted in Fig. 10, it offers significant emissions reductions compared to grey hydrogen while maintaining an LCOH comparable to on-site production.

6.2.5. Effect of constraints on safety performance on hydrogen-based system design

A further criterion that could strictly limit the decision-making is the company's desire to handle the most performant system configuration from a safety perspective. Indeed, the glass industry has only focused on mitigating occupational risks associated with extreme temperatures involved in the manufacturing process, which can lead to severe burns, or sharp materials, such as broken glass. The introduction of hydrogen brings additional challenges typical of the process industry, including higher flammability and explosion potential risks. Figs. 4 and 5 showed that the modules responsible for drastically decreasing the performance of the overall system are those related to the external hydrogen supply (truck delivery and storage), mainly due to the higher pressure compared to on-site production. The damage distances assessed for the considered trucks (TD1, TD2, TD3, and TD4) are 279 m, 302 m, 322 m, and 337 m, respectively. Guaranteeing such safety distances or accepting the associated risks is not always possible. Therefore, glass manufacturers could prefer a more expensive solution that does not require any high-pressure components, therefore relying solely on on-site production.

7. Conclusions

This study focused on supporting the transition necessary to decarbonize energy-intensive industries using hydrogen as an alternative cleaner fuel for combustion. A mathematical model was formulated to represent and compare different hydrogen-based supply system configurations, evaluating them in terms of cost, safety and environmental performance (refer to the Supplementary Material for detailed performance assessment). While the solution minimizing cost and enhancing safety performance aligns with the current natural gas-based scenario, it does not support achieving the net-zero emissions targets. Introducing hydrogen into the system brings trade-offs between crucial performance metrics, making it challenging to identify a universally optimal solution, as the best choice may depend on the specific application context. Therefore, this study analyzed various requirements companies may face, complemented by a sensitivity analysis of key external factors. Based on the findings and the conflicting considerations emerging from the analysis, the following recommendations are provided to practitioners:

- Full on-site hydrogen production offers the highest safety performance, whereas introducing even a small share of external supply leads to a substantial drop in safety levels. When relying on external supply, truck capacity plays a critical role. A higher truck capacity can reduce the HI by up to 26 % due to less frequent connection hose operations, but may increase the PI by up to 38 % due to higher delivery pressure and hydrogen content. Nonetheless, these higher PI levels can be mitigated by strategically locating the delivery area to account for the corresponding damage distances, which in this case range from 279 to 337 m. This underscores the importance of evaluating supply alternatives during the design phase, even if truck delivery is ultimately managed at the operational level.

- Electricity pricing is crucial in balancing on-site hydrogen production and external supply, directly influencing optimal electrolyzer sizing. In the current hydrogen market, where grey hydrogen remains dominant, external supply costs approximately 3.6 €/kg. High electricity prices (e.g., 0.10 €/kWh) make on-site production less competitive, increasing the LCOH to 6.4 €/kg. Conversely, at low electricity prices (e.g., 0.02 €/kWh), on-site production becomes more attractive, reducing the LCOH to 1.94 €/kg while also improving safety and environmental performance. In cases of high electricity price volatility, external supply may offer more stable and predictable hydrogen costs.

- Hydrogen market pricing should be carefully assessed for strategic electrolyzer decisions. High hydrogen prices (e.g., 5.3 €/kg) favor on-site production, reducing LCOH by 22 % compared to outsourcing. On the contrary, expanding internal capacity significantly raises hydrogen cost when a low-cost external hydrogen supply is available (e.g., 0.7 €/kg). Increasing internal capacity can stabilize costs and minimize undesired final product price fluctuations when external hydrogen prices are highly uncertain and variable.

- The investment decision in electrolyzer capacity must consider the carbon intensity of the available electricity source. Although hydrogen adoption eliminates direct CO_2 emissions from fuel combustion, using electrolysis powered by electricity with a carbon intensity above 0.11 kg CO_2e/kWh leads to a higher GWP than natural gas-based operations. This threshold becomes even lower when the system partially relies on externally supplied grey hydrogen. Mitigating this environmental drawback would require additional investment in renewable energy generation or a shift to a cleaner external hydrogen supply, both of which would further increase overall system costs.

- Outsourcing decisions should consider hydrogen market trends, particularly the type of commercially available hydrogen, as different options significantly vary in terms of environmental impact and production costs. A complete transition with external grey hydrogen supply can be cost-efficient under current carbon taxation, but its adoption leads to increased GWP levels by up to 68 % compared to natural-gas-based operations. On the contrary, green hydrogen external supply allows reducing the GWP by up to 76 %, while leading to an estimated LCOH of 6.7 €/kg. When it is preferable to outsource part of the hydrogen production to enhance system flexibility, blue hydrogen offers a balanced compromise between economic viability and environmental impact.

- When local renewable energy is limited, it is crucial to evaluate whether using a secondary energy source for achieving greater hydrogen integration offers better outcomes than prioritizing available green energy without necessarily maximizing hydrogen usage. In some cases, a lower hydrogen share with a smaller electrolyzer yields comparable environmental benefits while reducing operational costs and ensuring better safety performance.

8. Limitations and future developments

The mathematical model adopted to provide decision-making insights on the hydrogen system configuration is based on average data. The full complexity and the dynamics of real operations could be captured by extending and refining the model. Considering average values and the necessity to simplify the model led to the exclusion of a small buffer, which primarily serves to compensate for the expected fluctuations of the hydrogen production in the electrolyzer. Although the impact on the final results should be negligible, future studies could provide a model capable of incorporating variability and thus estimate the size of this buffer that can be included in the analysis. Considering the scope of the study, hydropower is the only renewable source considered for providing electricity to the electrolyzer. However, the model can be applied to any other renewable energy source by adjusting input data on costs and emissions. Additionally, the model can be easily extended to account for combinations of renewable energy sources, following a similar approach used to differentiate between the two electricity sources in this study. Similarly, the model is applied exclusively to a case study from the glass manufacturing sector. However, the general approach and mathematical formulation could be adopted to guide the transition of any other energy-intensive sector where hydrogen can replace natural gas in combustion. Some modifications to the system definition may be necessary before verifying whether the final insights from this study remain valid.

It is worth noting that the cost model used in this study has some limitations. Firstly, it does not quantify the unexpected costs of unforeseen truck delivery problems. In addition, risks are evaluated only from a safety perspective, while the financial consequences of accidents, which could damage workers or other assets, are not considered.

The inherent safety analysis used data from oil and gas as input for the likelihood of the Loss of Containment events due to the lack of available data for hydrogen. The main assumption is made on the credit factor considered for the electrolyzer system. A knowledge gap still exists regarding the failure analysis of the electrolyzer. However, the model can be easily adapted once more information is available. The inclusion of financial risks in the cost model would then be more feasible and accurate.

Lastly, the environmental performance assessment is limited to estimating greenhouse gas emissions, expressed as GWP. This approach is deemed appropriate given the aim of the study, which is to investigate decarbonization pathways and their implications for energy-intensive industries, particularly the glass sector. In the specific case of the electrolyzer, the water footprint WF has been estimated. However, costs and environmental impact associated with the water purification required to maintain the integrity of the electrolyzer are not included. Additionally, other environmental factors have been excluded from the scope of the study. Hence, the analysis could be extended in future work to incorporate a comprehensive life cycle assessment across different system configurations.

CRediT authorship contribution statement

Giulia Fede: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Giulia Collina:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Alessandro Tugnoli:** Writing – review & editing, Supervision, Methodology. **Marta Bucelli:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Daniel F. Silva:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Formal analysis. **Fabio Sgarbossa:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT to improve language readability. After using this tool/service, the author (s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.151373.

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