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Toward the application of the Risk-Based Maintenance approach to a hydrogen-fueled manufacturing plant

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ABSTRACT

Safety, reliability, and maintenance of hydrogen-based equipment, including Risk-Based Maintenance (RBM), have recently gained increasing attention, as hydrogen, while key to decarbonizing hard-to-abate sectors, raises safety concerns.

However, two literature gaps limit the development of risk-based strategies for hydrogen technologies. First, existing RBM methodologies do not account for hydrogen-specific components, such as electrolyzers, which differ from conventional equipment. Second, available studies on electrolyzer reliability remain largely qualitative or laboratory-scale.

This study addresses these gaps by proposing an adapted RBM methodology tailored to hydrogen-fueled manufacturing facilities. Integrating qualitative tools (e.g., FMEA) with probabilistic models (e.g., Bayesian Networks) enables comprehensive hazardous scenarios identification and likelihood estimation.

A conceptual layout of a glass furnace supplied by a 3 MW PEM electrolyzer is considered as a case study to demonstrate the feasibility of the adapted RBM framework in identifying high-risk components and enabling maintenance prioritization, potentially improving plant safety.

1. Introduction

The global energy sector is experiencing a significant shift to meet the emissions reduction target by 2050 in order to contrast climate change [1]. Hydrogen is a key player in this transition, and it is widely considered a solution for decarbonizing hard-to-abate sectors, including heavy industry, shipping, and aviation. Many industries that need high temperatures in their manufacturing processes expressed interest in introducing hydrogen. In particular, the glass, cement, steel, and aluminum sectors are investigating the possibility of replacing fossil fuels in their plants [1].

Hydrogen production represents a bottleneck in the supply chain. Global supply is increasing, but the dependence on fossil fuels is still prevalent [1]. Green hydrogen production must be prioritized: obtaining hydrogen through water electrolysis by exploiting renewable sources is considered a low-emission alternative, therefore essential to meet the net-zero emissions requirements. PEM and Alkaline water electrolyzers are the only commercialized technologies for industrial applications [2], but they are still more expensive and less established compared to production technologies relying on fossil fuels.

In addition to the technological development challenges to develop the entire supply chain, implementing hydrogen in different sectors introduces specific safety issues to be addressed. Hydrogen has a very low density (0.0899 kg/m3), low boiling point (20.4 K) [3] and a low ignition energy (0.017 mJ), while presenting a wide flammability range (4 - 75 % vol in air) [4]. Due to its small molecular size, it can diffuse and embrittle most metallic materials [5] leading to material degradation issues.

Dealing with a substance that can contribute to enhance and speed up equipment deterioration and, which can also lead to accidental

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injuries, loss of life and property damage, makes maintenance planning very important. Over the last few decades, maintenance management has undergone significant changes and improvements, aiming at optimizing the profitability of a plant, minimizing downtime, and maximizing equipment availability [6]. Corrective Maintenance (CM) involves acting after the failure has happened; this approach has been the most widely used for years, but the increase in reliability requirements has facilitated the shift towards Preventive Maintenance (PM) [7], which consists of acting before the failure happens. The simplest version of this approach is time-based (i.e., based on service age): maintenance is scheduled at regular intervals, regardless of the actual condition of the equipment. To overcome this limitation, the Condition-Based Maintenance (CBM) technique has been introduced. The equipment health is continuously monitored thanks to real-time data from sensing devices, and maintenance activities are carried out only when needed. Risk-Based Maintenance (RBM) and/or Risk-Based Inspection (RBI) schedules maintenance activities prioritizing higher risk devices [8], making them very suitable for maintenance management in sectors in which hazardous substances are handled.

Considering the critical properties of hydrogen, the latter management policy could be beneficial in ensuring operational safety and reliability in hydrogen systems. Recent studies dealt with the adoption of Risk-Based Inspection and Maintenance (RBI/M) for hydrogen-based solutions. Relevant examples include the application in the maritime sector [9], for hydrogen refueling station [10], and in the glass sector [8]. However, two knowledge gaps still remain. First, current standards and methodologies for RBI/M have not been fully adapted to the specific requirements of hydrogen technologies. This is particularly evident in the case of the electrolyzer, the core component for green hydrogen production [11]. Secondly, studies on electrolyzer reliability remain limited to qualitative or laboratory-scale analyses, with no comprehensive quantitative risk assessment available at the industrial scale [12].

Thus, to cover these two knowledge gaps, this study aims to develop a Risk-Based Maintenance approach tailored to hydrogen systems, demonstrated on an on-site hydrogen-fueled glass manufacturing plant. By adapting the Risk-Based Inspection approach provided by the API 580 [13], the methodology is designed to be transferable and applicable across multiple industrial sectors, supporting a safe adoption of hydrogen.

The proposed methodology contributes to the literature by extending RBM to hydrogen production systems and by providing the first quantitative safety analysis of an industrial-scale Proton Exchange Membrane electrolyzer (PEM). It also illustrates how Bayesian Networks can be used to represent Loss of Containment (LOCs) events, perform sensitivity analyses, and update risk models dynamically as new data become available. From a practical standpoint, the application to the glass sector highlights how the framework can guide asset managers in prioritizing maintenance activities based on risk rankings. By providing both methodological advances and operational insights, this work lays the groundwork for the future evolution of RBM into predictive maintenance strategies for hydrogen technologies.

Given the novelty and the complexity of on-site hydrogen production systems [12], a deeper preliminary analysis is necessary to identify available techniques and assess how they can be applied effectively. In the existing literature, many variations of this maintenance strategy are available. Therefore, a background section (Section 2) is necessary to support the application of this maintenance approach and to explain the gaps that this study aims to fill. Section 3 shows the Risk-Based Maintenance methodology adapted for use with new hydrogen systems. Section 4 presents the case study from the glass sector used to validate the methodology. Sections 5 and 6 provide and discuss the results of this approach. Finally, the conclusions are available in Section 7.

2. Background

This section introduces the background for this study. First, Section 2.1 briefly reviews the RBM approach, then Section 2.2 illustrates how the current study supports the adoption of the RBM methodology for hydrogen systems.

2.1. Risk-based maintenance

In the 1990s, Risk-Based Inspection and Maintenance emerged by combining maintenance and safety as a suitable way to maximize plant capacity, showing that safety and maintenance can work together effectively. Beyond the 2000s, this methodology has been increasingly investigated and applied in various fields, such as the onshore chemical and petrochemical industries and offshore and energy industries. The most established approach is the Risk-Based Inspection developed by the American Petroleum Institute (API) [13]. Fig. 1 shows the general flow chart of the approach. The main blocks are outlined below, supported by relevant studies. A non-exhaustive review of relevant studies is provided in Table S.1 in the Supplementary Material, where the different techniques adopted over the years are highlighted.

1. *Hazardous scenarios identification:* several techniques have been developed for this stage to identify hazardous events that may occur in a plant. Hazard and Operability Study (HAZOP) and Failure Mode and Effect Analysis (FMEA) are the most established systematic techniques that identify the possible failure of each component [14,15]. Fault tree analysis (FTA) is a deductive technique that starts from the hazardous event and identifies the combination of fundamental causes that can trigger it [16]. Maximum credible accident scenario (MCAS) is another systematic approach to screen and shortlist the scenarios most relevant to the scope of the study [17]. The API considers a list of reference equipment to identify the hazardous scenarios [18].
2. *Likelihood estimation*: this step aims to assign a probability of occurrence for each scenario. The most-used quantitative approach is based on giving a value to all the intermediate events of the fault tree analysis to calculate the probability of the final event [16]. Often, a single failure is modeled using the Weibull probability distribution in reliability analysis [19]. Bayesian Networks are also utilized in this step to offer more flexibility and the possibility to update in case new evidence arises [20]. In the standard provided by the API, the likelihood estimation is based on the combination of historical data for the generic failure frequency and a factor that takes into account various damage mechanisms, including internal and external thinning, internal and external stress corrosion cracking, high-temperature hydrogen attack, thermal, mechanical, and corrosion fatigue [18].
3. *Consequence analysis*: the objective is to quantify the potential impact of the selected failure scenario on property, environment and people. The quantitative analysis relies on mathematical models to evaluate the release of hazardous substances and then predict the characteristics of explosions and fires or human response to different levels of exposure to toxic chemicals [17,21,22]. These impacts are sometimes expressed in terms of loss of money [16,23]. Both the likelihood estimation and consequence assessment stages can be addressed qualitatively by assigning, respectively, frequency and severity indexes [14,24,25].
4. *Risk evaluation:* based on the approaches and results of the consequence analysis and the likelihood estimation, the risk can be estimated. Many approaches calculate it by multiplying the likelihood of a selected scenario and the monetary value of its associated consequences [16,23]. Often, the risk matrix is used as a visual tool showing the impact of an event on the x-axis and the likelihood on the y-axis [22,25]. The risk priority number (RPN) is typically used

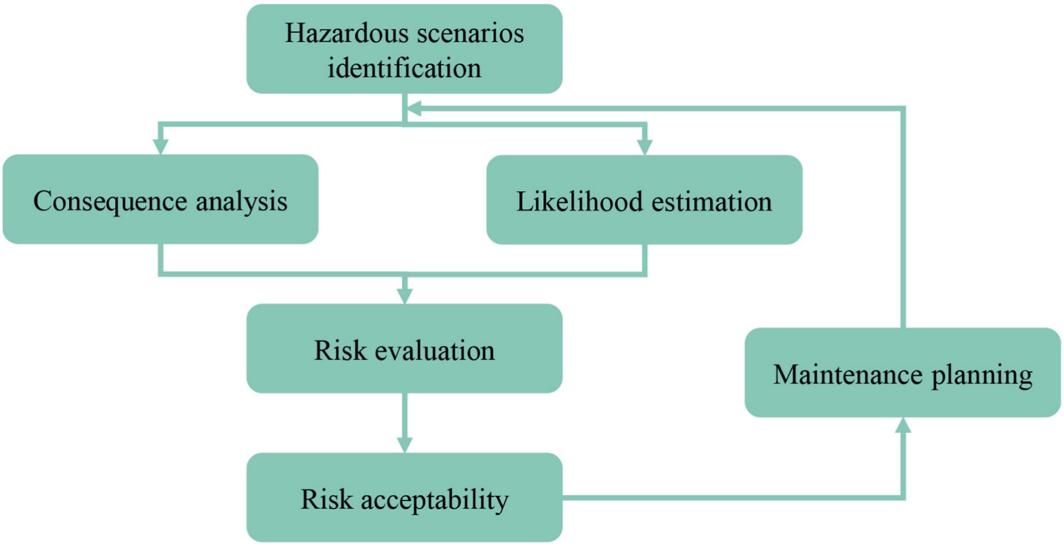


Fig. 1. General block flow diagram for the Risk-Based Maintenance approach.

for qualitative analysis [6], and is the combination of the indexes assigned to consequences and probabilities.

5. *Risk acceptability*: once the risk is evaluated, some acceptability criteria are required. There are a few present in the literature: ALARP (as low as reasonably possible), Dutch acceptance criteria, and USEPA acceptance criteria [17]. When risk is measured in monetary terms, its acceptability is also evaluated through an economic lens.
6. *Maintenance planning*: the equipment that does not meet the risk criteria should be included in the maintenance plan. When the quality of likelihood estimation allows, the maintenance plan is developed by a reverse analysis targeting a specific probability of failure [17,21]. In other cases, the criteria focus on cost minimization [24]. A proper maintenance plan is not developed in all the quantitative analyses, but some relevant information from the risk evaluation is still used to prioritize maintenance activities [25].

2.2. Gaps and research objective

All the studies mentioned in the previous section apply the RBM or RBI policies to case studies within the onshore chemical and petrochemical industry, such as a reforming reaction system and a sour crude oil processing plant. While these contributions demonstrate the effectiveness of risk-based methodologies in those contexts, they rely on sector-specific assumptions, degradation mechanisms, and operational data. On the other hand, emerging hydrogen systems present different challenges not only in terms of material behavior and failure modes, but also due to the introduction of new components, such as fuel cells and electrolyzers, for which operational experience and reliability data are still limited [11].

Recently, a few studies have been conducted to develop a RBI methodology capable of taking into account the specific hydrogen interaction with materials, evaluating the degrading effects of hydrogen embrittlement and hydrogen-enhanced fatigue [26,27]. Despite these improvements, the API RBI approach is still limited in scope, as it is specifically tailored to equipment common in the oil and gas sector. Consequently, it does not resolve the fundamental limitation of applying this approach to hydrogen systems, which involve novel components not covered by traditional references. The LOCs for hydrogen-specific components are not listed in the API RBI [18]. Other studies applied these maintenance policies to hydrogen systems, excluding non-conventional components: Giannini et al. [9] applied the RBI to a hydrogen-fueled fishing vessel, focusing on the storage and piping, and excluding the fuel cell system; Collina et al. [8] applied the RBM to a hydrogen-fueled glass plant, considering only the external supply, thus not including the electrolyzer system. This reveals a first gap: the lack of an RBM framework that systematically integrates hydrogen-specific components. Therefore, in the context of hydrogen technologies, it is necessary to take a step back and reconsider the entire RBM framework for identifying LOCs for hydrogen-specific components. A proper adaptation is required to account for the unique configurations and operational characteristics of hydrogen systems.

At the same time, the literature on electrolyzer failure and reliability remains at an early stage. Tuhi et al. [12] reviewed the analysis of failure and reliability assessment for the hydrogen industry involving fuel cells and electrolyzers. Their study shows that, so far, publications considering the whole electrolyzer system (i.e., including the balance of plant) are only qualitative, while some quantitative analyses are available for fuel cells [12]. Subsequently, two studies from the SyRRA Lab were published on a lab-scale PEM electrolyzer (power rating in the order of kW and hydrogen production in the order of 0.1 kg/h), marking a significant step toward the understanding of electrolyzer failure mechanisms. Specifically, Wismer et al. [28] present a qualitative analysis of the main failure modes, laying the groundwork for a better understanding of system vulnerability. Building on this, Al-Douri et al. [29] developed fault trees to explore hydrogen release scenarios. However, a second gap persists: the absence of a comprehensive quantitative analysis of an industrial-scale electrolyzer (systems in the order of MW, typically associated with hydrogen production rates on the order of 10 kg/h), including scenarios where explosive mixtures may form.

Table 1 shows how the current study relates to other available studies on RBM and on electrolyzer analyses. The vast majority of the RBI/M studies are related to other industrial applications, while only three are related to hydrogen technologies (hydrogen RBI/M). Still, none of them addresses novel components such as fuel cells and electrolyzers.

The objective of this study is to address both the mentioned gaps by proposing an adaptation of the RBM methodology specifically for hydrogen production systems, with the aim of identifying and assigning an occurrence probability to credible release scenarios involving the electrolyzer. This enables the integration of the electrolyzer into the overall risk ranking, allowing maintenance interventions to be prioritized effectively. Furthermore, this effort serves as an opportunity to provide data for both the probability of failure and consequence assessment in industrial-scale electrolyzer applications. A Bayesian approach is proposed to ensure flexibility and continuous updating as new data becomes available, making the methodology adaptable to the

Table 1
Relevant studies on Risk-Based Maintenance and failure analysis of electrolyzer systems.

		Risk-Based Maintenance			Failure analysis of electrolyzers			
Type of study	References	Other industry	Hydrogen industry	Novel components (electrolyzer, fuel cells)	Type of study	Electrolyzer scale	Balance of Plant included	Integration with RBM
RBI/M	[17]	General industrial application						
	[30]	Energy industry						
	[31]	Energy industry						
	[21]	Generial industrial application						
	[19]	Energy industry						
	[24]	Onshore chemical and petrochemical industries						
	[16]	Onshore chemical and petrochemical industries						
	[23]	Onshore chemical and petrochemical industries						
	[22]	Onshore chemical and petrochemical industries						
	[25]	Onshore chemical and petrochemical industries						
	[32]	Onshore chemical and petrochemical industries						
	[14]	Onshore chemical and petrochemical industries						
	[15]	Offshore						
	[33]	Onshore chemical and petrochemical industries						
Hydrogen RBI/M	[9]	Maritime	✓					
	[10]	Hydrogen refueling station	✓					
	[8]	Manufacturing	✓					
Hydrogen reliability/ risk/safety	[34]				Qualitative	Laboratory		
	[35]				Quantitative	n.s.		
	[36]				Qualitative	Industrial	✓	
	[28]				Qualitative	Laboratory	✓	
	[29]				Quantitative	Laboratory	✓	
	This study	**Manufacturing**	✓	✓	**Quantitative**	**Industrial**	✓	✓

evolving nature of hydrogen technologies.

3. Adapted Risk-Based Maintenance method

The integration of hydrogen systems requires an adaptation of the Risk-Based Maintenance methodology to enable a more accurate and relevant assessment. In particular, hydrogen-specific components (e.g., electrolyzers and fuel cells) should not be approached in the same way as conventional equipment. While components like pipes, valves, tanks, and pumps benefit from well-established operational data and standardized reliability models [11], hydrogen technologies exhibit distinct behaviors that call for a tailored assessment framework. The proposed method is shown in Fig. 2, and each step is described as follows.

Step 0. System analysis and equipment inventory: based on the case study under analysis, the system is defined, and all the equipment handling hazardous materials is investigated. In this step, it is necessary to distinguish which equipment is referable to conventional units (such as pipes, vessels, compressors) and which are non-conventional ones, based on the availability of information and frequency data on LOC events as this distinction determines two different paths for the next steps.

Step 1. Hazardous scenarios identification: this step aims at identifying LOCs and differentiates between conventional (Step 1a) and non-conventional equipment (Step 1b). The conventional API RP 581 [18] classification differs among small, medium, and large hole sizes for continuous releases and rupture for instantaneous releases. Alternatively, the guidelines from the TNO Purple Book [37] provide a classification of loss of containment sizes for each type of equipment. The specific units outside of the conventional equipment (e.g., pipes, vessels, etc …) should be analyzed systematically. For this reason, a qualitative Failure Mode and Effects Analysis (FMEA) is essential to build Fault Trees through a reverse procedure. In this way, the LOC events are identified by combining the failure modes of the components, which then become the basic events of the FTs. The FMEA follows the classification of releases adopted for the LOC definition of conventional equipment, ensuring consistency.

Step 2. Likelihood estimation: the generic failure frequencies associated with the LOC events are derived from the same references used in Step 1 for conventional equipment (Step 2a). In this preliminary adaptation of the methodology to hydrogen technologies, time-dependent degradation mechanisms are excluded from the analysis. In the API RBI framework [18], the time-dependent contribution to the probability of failure is expressed through the damage factor. Since methodologies for evaluating the damage factor in hydrogen applications are not yet fully standardized or validated, the consideration of this parameter is excluded from the present study, and its potential effect and contribution are discussed in the Discussion section. The FTs developed for non-conventional units are mapped into a Bayesian Network to estimate the annual probability of failure (Step 2b). Compared to a FT, a BN is a more flexible tool, allowing to model non-binary states and conditional probabilities, ensuring higher flexibility. Similarly, BN provides the users with the possibility of having an updatable tool in case of new evidence, which is pivotal considering the emerging nature of the system for which the methodology is tailored. The probabilities of the basic

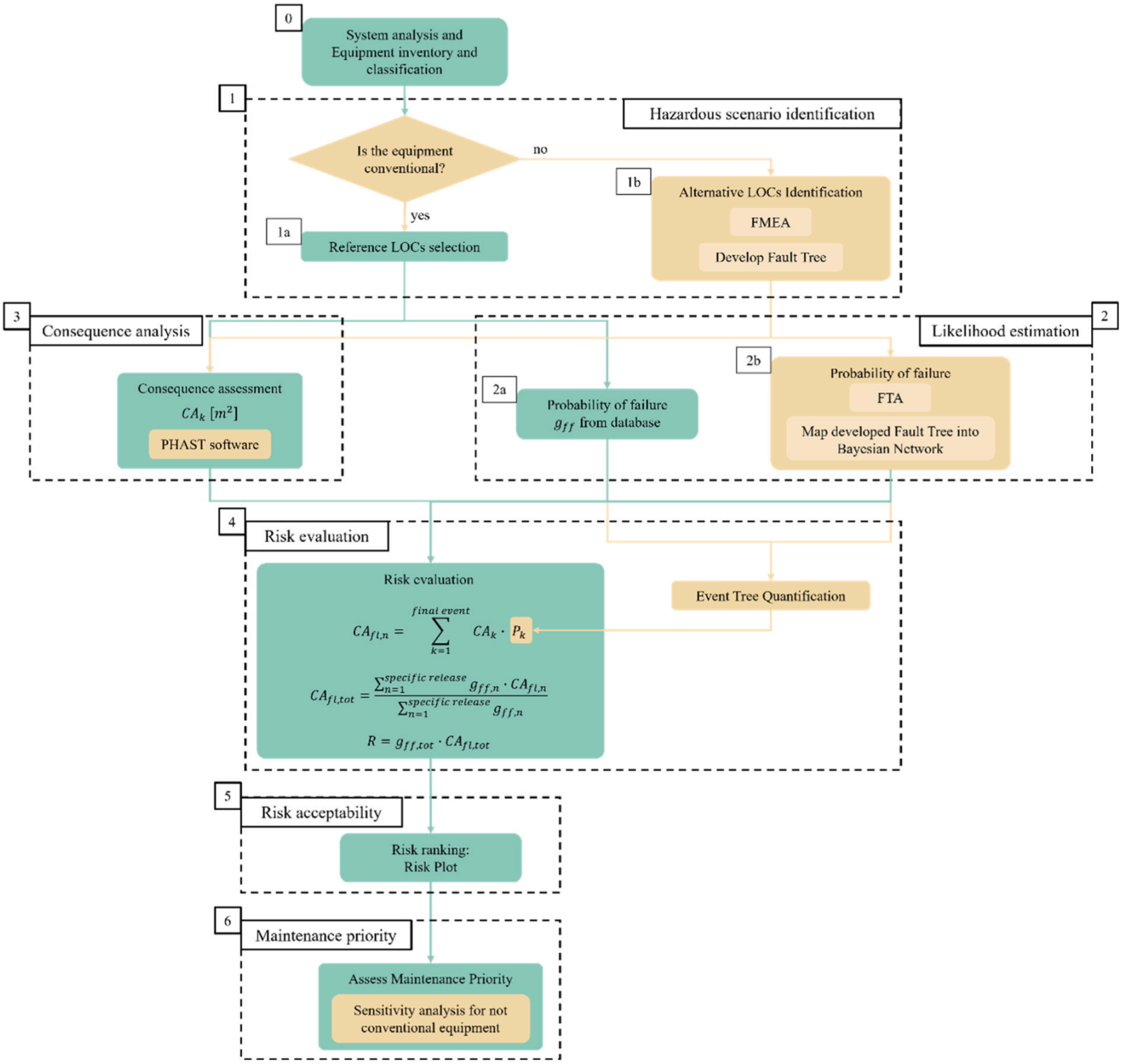


Fig. 2. Methodology adopted in this study. The green blocks follow the framework of the conventional Risk-Based Inspection by the API [18]. The beige blocks are the additional steps of the proposed approach. The lighter internal blocks are used solely to distinguish the specific tools employed within each step. The black dashed blocks correspond to the general block flow diagram of the RBM approach. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

events are still taken from oil and gas databases [37,38]. This approach is particularly valuable as monitoring tools are implemented in hydrogen systems [39], allowing the model to be updated with operational data. The GeNIe Modeler [40] is used to perform the analysis. This dual approach ensures that both conventional and novel risks are rigorously assessed within a unified risk management framework.

Step 3. Consequence analysis: a more detailed consequence analysis than the one provided by the API RBI 581 methodology is performed using the commercial software Phast 8.9 [41], which calculates the damage distances for each equipment, considering threshold levels associated with each potential final event. Hydrogen concentration equal to the lower flammability limit (LFL) in air for flash fires, thermal radiation of 12.5 kW/m^2 for fires, and overpressure of 0.14 bar for explosions are the reference values corresponding to the onset of lethal effects, as they are commonly used as personnel fatality criteria for risk assessment [42]. A LFL value of 4% vol hydrogen in air is suggested for the assessment. Although variability in hydrogen LFL has been reported in the literature depending on experimental and ignition conditions [43], the selected value corresponds to the lower bound of the reported range and represents the most widely cited reference value [44,45]. The adoption of this minimum value ensures a conservative estimation of hazardous effects in the risk assessment.

The effects are evaluated at 1 m height from the ground level, and proper environmental conditions should be evaluated. In the instance of events that can not be simulated with the software, the TNO Yellow Book is used [46]. Each equipment mentioned in the process industry guidelines could release in different sizes and types (instantaneous or continuous, leak or full bore), and the release could develop into different final events (jet-fire, explosions, flashfires, fireballs). The output of this step consists of the impact areas (CA_k) corresponding to each final event of every LOC associated with each equipment.

Step 4. Risk evaluation: to assign a unique value to each equipment (CA_{fl}), the frequencies of each type of release ($g_{ff,i}$) and the probabilities of generating a final event (P_k) are used to weigh the consequences of a flammable release, as shown in Equations (1) and (2)

[18]. The P_k are evaluated through an Event Tree Analysis, and using the ignition probability model proposed by Ref. [47], which is specific for hydrogen. The risk associated is calculated as the combination of the results of the consequence analysis (CA_{fl}) and the sum of the frequency of all the releases for each equipment ($g_{ff,tot}$).

$$CA_{fl,i} = \sum_{k=1}^{final\ event} CA_k \cdot P_k \tag{1}$$

$$CA_{fl} = \frac{\sum_{i=1}^{specific\ release} g_{ff,i} \cdot CA_{fl,i}}{\sum_{i=1}^{specific\ release} g_{ff,i}} \tag{2}$$

$$R = g_{ff,tot} \cdot CA_{fl} \tag{3}$$

Step 5. Risk acceptability: the equipment is ranked and assigned with a risk level value (i.e., low, medium, medium-high, and high) defined in API 581 [18] and listed in Table 2. The numerical gaps between the ranges shown in the table correspond to transition zones, representing values where the risk level gradually shifts from one category to the next.

Step 6. Assess Maintenance Priority: based on the ranking of the step 5, priority maintenance activities are defined. Specifically, devices with a higher risk should be maintained or inspected more frequently. Alternatively, if the risk level exceeds the threshold, redesign can be a solution to achieve an acceptable risk level. To further support decision-making, especially for non-conventional equipment, a sensitivity analysis of the developed Bayesian network (e.g. through GeNIe Modeler software) is performed to identify the most critical sub-components, and to evaluate the robustness of the results with respect to uncertainties in the input reliability data.

4. A case study from the glass sector

This section presents the case study to illustrate the proposed methodology. The glass sector is one of the energy-intensive industries that need to be decarbonized [1]. The first subsection of this chapter describes the general layout, while the second focuses specifically on the electrolyzer, which is the non-conventional component of the system. In this way, the first step of the methodology is already addressed, and the non-conventional component requiring the alternative methodological path is identified.

4.1. General description of the plant

The hypothesized layout of the hydrogen supply system feeding the glass furnace is shown in Fig. 3. The system is based on a conceptual design developed for experimental hydrogen testing campaigns within the H2GLASS project [48]. The fuel demand of the furnace is calculated based on an assumed production of 100 t_{glass}/d and an average energy consumption of container glass furnaces of 5150 MJ/t_{glass} [49], resulting in around 600 Nm^3/h of natural gas, which corresponds to 2000 Nm^3/h of hydrogen. Hydrogen is produced locally at 30 bar through a 3 MW PEM electrolyzer (600 Nm^3/h). The selection of this type of electrolyzer is due to the necessity of using green hydrogen to decarbonize the glass industry and the improved integration with renewable energy sources compared to other alternatives [50]. The 9 m^3 buffer helps manage fluctuations in production and ensures a continuous flow. An external supply is required to cover the complete switch to hydrogen instead of natural gas. Hydrogen is delivered as a compressed gas from a truck at 200 bar. A two-stage pressure reduction is required before entering the storage system, which compensates for potential delays in truck deliveries. A pressure control system is necessary before feeding the furnace which operates only slightly above atmospheric pressure. Additional details on the operating conditions are available in Table S.3 in the Supplementary Material.

Table 2
Risk ranking criteria.

Risk value [m^2•ev/year]	Risk level
<2.8E-03	Low
2.8E-02 - 2.8E-01	Medium
2.8 - 2.8E+01	Medium high
>2.8E+02	High

4.2. Electrolyzer unit

An electrolyzer system includes not only the electrolyzer stack, but other components that supply water and transport oxygen and hydrogen. This entire system is referred to as the balance of plant (BoP). Al-Douri and Groth [51] highlighted the lack of publicly shared details about these systems and the challenge in properly understanding the system, which is essential for conducting quantitative risk analysis (QRA). Fig. 4 shows a simplified P&ID of a PEM electrolyzer, including the BoP. The system configuration was defined based on a review of peer-reviewed literature, publicly available information from major electrolyzer manufacturers, and consultation with experts from both academia and industry working on hydrogen technologies. The main literature sources used to define the configuration are reported in Table S.2 in the Supplementary Materials. Alternative layouts reported in literature and industrial practice were considered, particularly regarding gas-liquid separation strategies and stack configuration. While some systems employ a single water-hydrogen separator [50], others use two separation stages to reduce the risk of hydrogen contamination entering the oxygen circuit and to improve operational reliability [52]. In addition, different stack configurations were reviewed based on typical industrial electrolyzer layouts. Based on literature evidence and expert consultation, a configuration with two gas-liquid separation stages and multiple stacks was adopted in this study.

The components considered in the electrolyzer unit system are organized by four functional groups, as proposed by Wismer et al. [28]. The first functional group (FG 1), showed in black in Fig. 4, is the water supply and separation; the second group (FG 2), coded in red, is responsible for delivering hydrogen from the electrolyzer to the final user; the third group (FG 3), in blue, transports and delivers oxygen; the fourth group (FG 4), coded in green, is electrolysis stack itself. The entire equipment list per functional group is shown in Table 3.

Water enters the system (PW1) and reaches the oxygen-water separator (OWS1). From there, it is pumped (PW2, PW3) into the electrolyzer stack (ES1), producing hydrogen and oxygen. From the anode side, an oxygen-water mixture leaves the stack (PO1) and enters the oxygen-water separator (OWS1), which is responsible for oxygen separation and outside delivery (PO2). The stream is always cooled down before entering the stack (HE1) to balance the power losses. The cathode side works at higher pressure (30 bar) to optimize the overall cost of the system [53], thanks to a back pressure regulator (BPR1). From the stack, hydrogen (PH1) enters the separation stage, which occurs in two steps (HWS1 and HWS2) to enhance the safety of the system, minimizing the amount of hydrogen going back to the OWS1 (PW7). The hydrogen stream from the first separator (PH3) goes to the heat exchanger (HE2) to reduce the dew point and then to the deoxidizer (HDO1) and drying system (HDR1) before being delivered (PH3). Between the two separation stages, the water-hydrogen mixture reduces its pressure (RV2). From the low-pressure separator, a minimal loss of hydrogen is vented (PH2). To achieve a production rate of 600 Nm^3/h, three electrolysis stacks of 1 MW, each contained in a dedicated container, are considered.

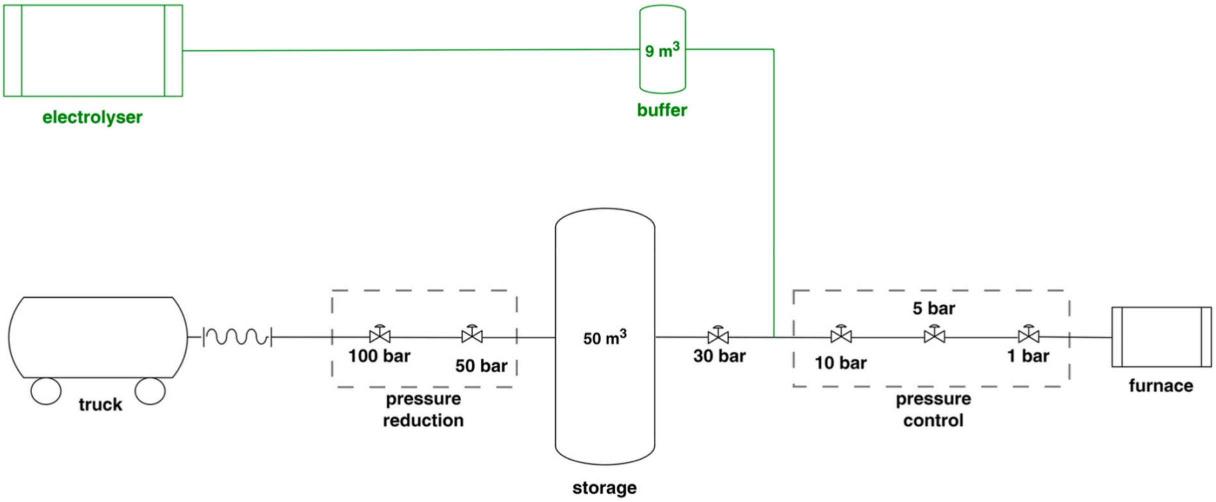


Fig. 3. Plant layout for hydrogen supply to the furnace. The green part is required to ensure on-site hydrogen production. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

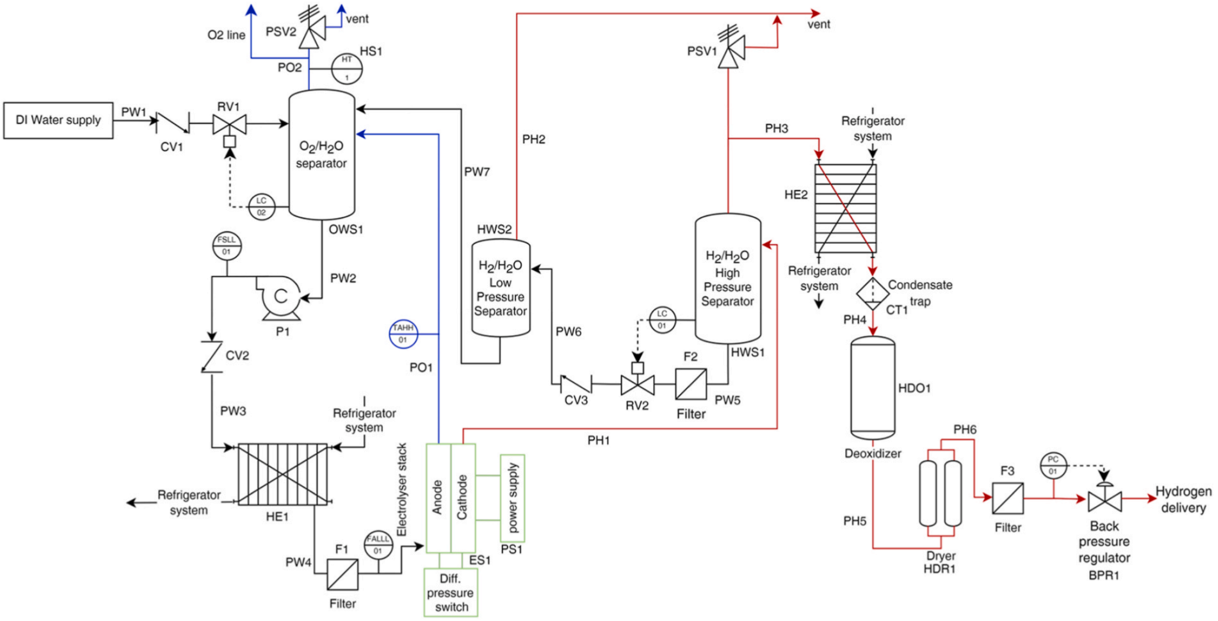


Fig. 4. P&ID for a general PEM electrolyzer system. Black line: water functional group; red line: hydrogen functional group; blue line: oxygen functional group; green line: electrolyzer stack functional group. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4.3. Assumptions for consequence analysis

In the absence of a specific geographical reference location and, consequently, of a site-specific wind distribution (as adopted in Ref. [33]), a set of representative environmental conditions is defined to ensure a comprehensive and robust assessment. Three atmospheric scenarios are selected based on the Pasquill stability classes reported in the Supplementary Material.

- Pasquill class F (stable atmospheric conditions) with low wind speed (1.5 m/s);
- Pasquill class D (neutral atmospheric conditions) with moderate wind speed (5 m/s);
- Pasquill class A (unstable atmospheric conditions) with low wind speed (1.5 m/s);

Among these, class F with low wind speed is commonly adopted in similar studies, as it generally provides conservative results in dispersion analyses [54–57]. Class D is selected because it represents frequently occurring atmospheric conditions according to the Pasquill stability classification [58,59].

For classes F and D, two sets of ambient thermohygrometric conditions are considered: −5 °C with 85% relative humidity and 20 °C with 65% relative humidity. These parameter combinations are selected to represent meteorological conditions characteristic of cold-climate regions and warm-climate regions, respectively, thereby extending the applicability of the analysis across different macro-climatic contexts.

To complete the assessment, class A is also included. In this case, ambient conditions representative of daytime unstable atmospheric regimes are adopted, namely −1 °C with 85% relative humidity and 29 °C with 65% relative humidity, again reflecting cold- and warm-climate scenarios.

Table 3
Component list for PEM electrolyzer divided into functional group.

Water functional group		Hydrogen functional group		Oxygen functional group		Electrolyzer stack functional group	
ID	Component	ID	Component	ID	Component	ID	Component
OWS1	Oxygen-water separator	HE2	Heat exchanger	PO1, PO2	Piping	ES1	Electrolysis stack
HWS1	High-pressure hydrogen-water separator	CT1	Condensate trap	HS1	Hydrogen sensor	PS1	Power supply
HWS2	Low-pressure hydrogen-water separator	HDO1	Deoxidizer	PSV2	Pressure safety valve		
HE1	Heat exchanger	HDR1	Dryer	TAHH	High high temperature alarm		
CV1, CV2, CV3	Check (non-return) valve	F3	Filter				
F1, F2	Filter	BPR1	Back pressure regulator				
P1	Centrifugal pump	PSV1	Pressure safety valve				
RV1, RV2	Regulating valve	PH1, PH2, PH3, PH4, PH5, PH6	Piping				
PW1, PW2, PW3, PW4, PW5, PW6, PW7	Piping						
FSLL	Low low flow switch						
FAHH	High high flow alarm						

5. Results

This section presents a comprehensive analysis of the application of the adapted RBM methodology to a hydrogen-fueled glass plant. For this reason, the results are presented following the structure of the methodology.

5.1. Hazardous scenarios identification

In line with the methodology, the case study considers different analytical paths for the identification of conventional and alternative LOCs. First, data for the conventional equipment are collected from the literature (Subsection 5.1.1), addressing Step 1a of the methodology. Then, the electrolyzer used for on-site green hydrogen production, which is not referrable as a conventional equipment, requires a dedicated, in-depth assessment (Subsection 5.1.2). Thus, it is necessary to investigate the electrolyzer system with the objective of identifying potential hazardous scenarios, addressing Step 1b of the methodology.

5.1.1. LOCs for conventional equipment

The LOC events for conventional components are directly collected from the literature. Table 4 lists the equipment required to ensure the hydrogen supply to the glass furnace, with the corresponding associated equipment, which is the reference essential to retrieve data from the literature [37].

Table 4
Hazardous scenarios identification and corresponding occurrence probability for the standard equipment in the new layout of the glass manufacturing plant.

Equipment	Reference equipment	LOCs	Probability (1/year)
Buffer	Pressure vessel	Catastrophic failure	5.00E-07
		10 mm leak	5.00E-07
		Continuous 10min	1.00E-05
Electrolyzer line	Pipe	10% leak	5.00E-04
		Full rupture	1.00E-04
Truck hoses	Hose	10% leak	9.19E-02
		Full rupture	9.59E-03
100 bar reduction	Pipe	10% leak	1.00E-05
		Full rupture	2.00E-06
50 bar reduction	Pipe	10% leak	1.00E-05
		Full rupture	2.00E-06
Storage vessel	Pressure vessel	Catastrophic failure	5.00E-07
		10 mm leak	5.00E-07
		Continuous 10min	1.00E-05
30 bar reduction	Pipe	10% leak	2.50E-05
		Full rupture	5.00E-06
10 bar reduction	Pipe	10% leak	1.00E-05
		Full rupture	2.00E-06
5 bar reduction	Pipe	10% leak	1.00E-04
		Full rupture	2.00E-05
Line to burner	Pipe	10% leak	1.00E-05
		Full rupture	2.00E-06

5.1.2. LOCs for the electrolyzer

The electrolyzer system is subjected to a Failure Modes and Effects Analysis (FMEA). After defining the electrolyzer configuration considered in this study, the FMEA was adapted from the available literature [28] to reflect the specific components and subsystems of the industrial-scale system analyzed. The failure mode list was expanded to account for additional equipment and operational aspects relevant to industrial installations. Additional failure modes were incorporated through consultation with experts involved in hydrogen technologies, including both academic researchers and industrial practitioners operating electrolyzer systems. In particular, this process supported the inclusion of system elements, such as an additional hydrogen-water separation stage and dedicated control systems for the electrolyzer, along with their associated potential failure modes. The systematic analysis of the components, shown in Table 3, enables the identification of relevant hazardous scenarios, such as the release of hydrogen and the formation or release of an explosive mixture of hydrogen and oxygen. By critically reassembling the shared causes of each scenario, the fault trees are constructed to map failure pathways. The developed fault trees are available in the Supplementary Material. Pure hydrogen can be released into the environment from each component of the hydrogen system, resulting in several final scenarios. Additionally, hydrogen can be released directly from the electrolyzer stack into the container, resulting in pressurization and the formation of an explosive atmosphere inside the equipment, which is not designed to handle this scenario, leading to an explosion. One of the critical features of the electrolyzer is the potential for the formation of an explosive mixture, as hydrogen and oxygen are separated only by the membrane within the stack. Membrane degradation would result in hydrogen crossover into the oxygen circuit, potentially causing an internal explosion. If, in addition, a component of the oxygen side fails, this could lead to the release of a flammable mixture. The preferential direction of crossover toward the oxygen side is due to the hydrogen circuit typically operating at a higher pressure. Conversely, oxygen crossover into the hydrogen circuit is only considered possible in the event of membrane failure and a pressure drop in the hydrogen side. It is also important to highlight that the release of an explosive mixture from the hydrogen side would require the simultaneous occurrence of the oxygen crossover and the release from the components, resulting in a very low probability. Moreover, the consequences would be less severe than those of a pure hydrogen release, since the mixture would contain a lower proportion of the flammable component. Therefore, this scenario has not been included among the main ones considered.

5.2. Likelihood estimation

As the previous step, the evaluation of the probability of failure requires two different paths. Subsection 5.2.1 addresses Step 2a of the methodology, providing the probability of failure for conventional equipment. Subsection 5.2.2 addresses Step 2b of the methodology, assigning quantitative data to the developed fault trees and mapping them in a Bayesian Network.

5.2.1. Likelihood estimation for conventional equipment

The probabilities of failure for conventional equipment are directly retrieved from the literature [37], as for the LOCs identification. The collected data are available for each LOC in Table 4.

5.2.2. Likelihood estimation for the electrolyzer

To quantify the top event of the developed fault trees, the probabilities of the basic events are evaluated over a year, considering 8760 h of operation without downtime. The limited availability of specific data for hydrogen components [60] necessitates continued reliance on databases from the oil and gas sector for system analysis. Although these databases do not reflect typical hydrogen degradation mechanisms, they have already been used for different contexts, such as a quantitative risk assessment for a refueling station [61], or for hydrogen fuel cell forklifts [62].

Table 5 shows the data used in the current study. When referring to the release to the environment, the loss of containment from the TNO Purple Book [37] are considered. Then, the quantitative data for the oxygen components are taken from the same reference, while the quantitative data for the hydrogen components are collected from HyRAM+ [63].

The quantitative results for each release scenario and sub-scenario (LOC) are summarized in Table 6 as probabilities. The first two sub-scenarios of pure hydrogen releases to the environment refer to releases from pipes. This category also includes other components of the piping (e.g., filters, valves, flanges). The releases from pipes are classified as minor (10 % of the diameter) and full bore to ensure consistency with the reference sources for conventional equipment [37]. The other sub-scenarios refer to the hydrogen-water separator. Also in this case, three different sub-scenarios are selected to be consistent with the LOC shown in Table 4. The same considerations are valid for the sub-scenarios corresponding to hydrogen-oxygen mixture release to the environment from the oxygen circuit.

Table 5
Quantitative data used to quantify the Fault Tree.

Description	Probability (1/year)	Data source
Failure BPR1	3.57E-02	[38]
Erratic output P1	1.39E-02	[38]
Abnormal power supply ES1	1.90E-02	[64]
Plugging	1.31E-03	[38]
Upstream release	1.33E-05	[63]
Fail to operate P1	1.81E-02	[38]
Spurious stop P1	3.21E-02	[38]
Fail closed CV2	1.14E-03	[38]
Insufficient heat transfer in HE1	6.13E-03	[38]
Internal leak O2 in ES1 (pinhole)	1.37E-12	[65]
Fail to open BPR1	1.73E-02	[38]
Fail to operate SV1	4.38E-04	[38]
Fail closed CV3	1.14E-03	[38]
Fail to operate PSV1	7.88E-03	[38]
Gasket failure	1.75E-03	[38]
Temperature switch failure	3.18E-02	[38]
Pressure switch failure	9.20E-03	[38]
Flow switch failure	3.18E-02	[38]
PLC failure	8.67E-02	[38]

Table 6
Loss of Containment Events resulted from the electrolyzer system analysis.

Scenario	Sub-scenarios (LOC)	Probability (1/year)
Hydrogen release to environment from H_2 circuit	10% leak from pipes	6.30E-03
	Full bore from pipes	6.20E-03
	10 mm leak from HWS1	1.00E-04
	10 min leak from HWS1	5.00E-06
	Catastrophic rupture from HWS1	5.00E-06
H_2–O_2 mixture release to environment from O_2 circuit	10% leak from pipes	1.70E-06
	Full bore from pipes	5.70E-07
	10 mm leak from OWS1	2.10E-06
	10 min leak from OWS1	1.10E-07
	Catastrophic rupture from OWS1	1.10E-07
Internal explosion in O_2 circuit	Physical explosion	2.10E-02
Internal explosion in H_2 circuit	Physical explosion	7.60E-04
Stack container pressurization and release	Confined explosion	5.25E-03

As mentioned above, the quantitative results of the fault trees are strictly dependent on the data used from the databases. As the acquisition of reliable hydrogen-specific data is still ongoing, the databases exploited in this study are not always specific to electrolyzer systems. Therefore, Fig. 5 provides a flexible framework that can be updated once new operational data, failure evidence, or system configurations specific for the electrolyzer unit become available. Mapping the generated fault trees in a BN enables this dynamic incorporation of new information.

5.3. Consequence analysis

The impact areas for each final event are evaluated through Phast software, considering the threshold highlighted in Section 3 and considering different atmospheric conditions, as described in Section 4.3. Some scenarios related to the electrolyzer system are not processed with the software. In particular, the internal explosions in the hydrogen and oxygen circuits are modeled as burst rupture due to an internal reaction, following the procedure in the TNO Yellow Book [46]. The oxygen side is assumed at the lower flammability level, while the hydrogen side at the upper flammability limit. The consequences related to the stack pressurization are calculated considering a confined explosion of a stoichiometric flammable mixture in the empty volume of the container, as in Ref. [46].

The details of the consequence analysis results are summarized in Tables S.5-S.7 in the Supplementary Material, where the impact areas are presented. Fig. 6 shows the results obtained from Phast for the catastrophic rupture of the storage vessel, provided as a representative example. For each final event, the area corresponding to the threshold values defined in Section 3 are calculated.

The consequence analysis in this study is performed using the software Phast, primarily due to its capability to model a wide range of LOCs and to represent releases from different types of process equipment. This flexibility is particularly relevant to the present work, which considers multiple releases from different components. However, it should be noted that other tools are available for analyzing accidental release scenarios and for consequence assessment such as EFFECTS [66],

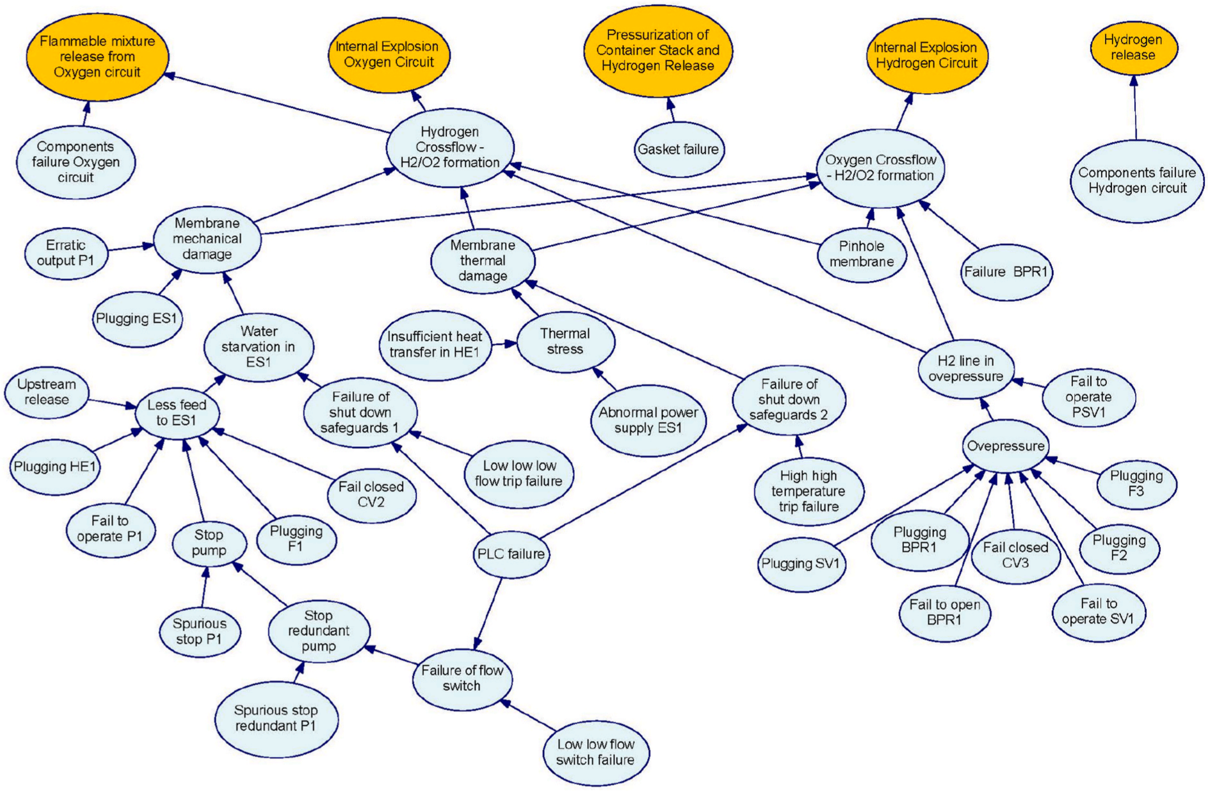


Fig. 5. Bayesian Network developed through the GeNIe Modeler to summarize the final scenarios for the electrolyzer system.

ALOHA [67], and HyRAM [68]. A comprehensive comparison among different modelling tools is beyond the scope of the present study and would require a dedicated analysis. Nevertheless, additional information on the use of alternative tools and their potential application to the considered scenarios is provided in Section S.5 of the Supplementary Material, including an illustrative example.

5.4. Risk evaluation

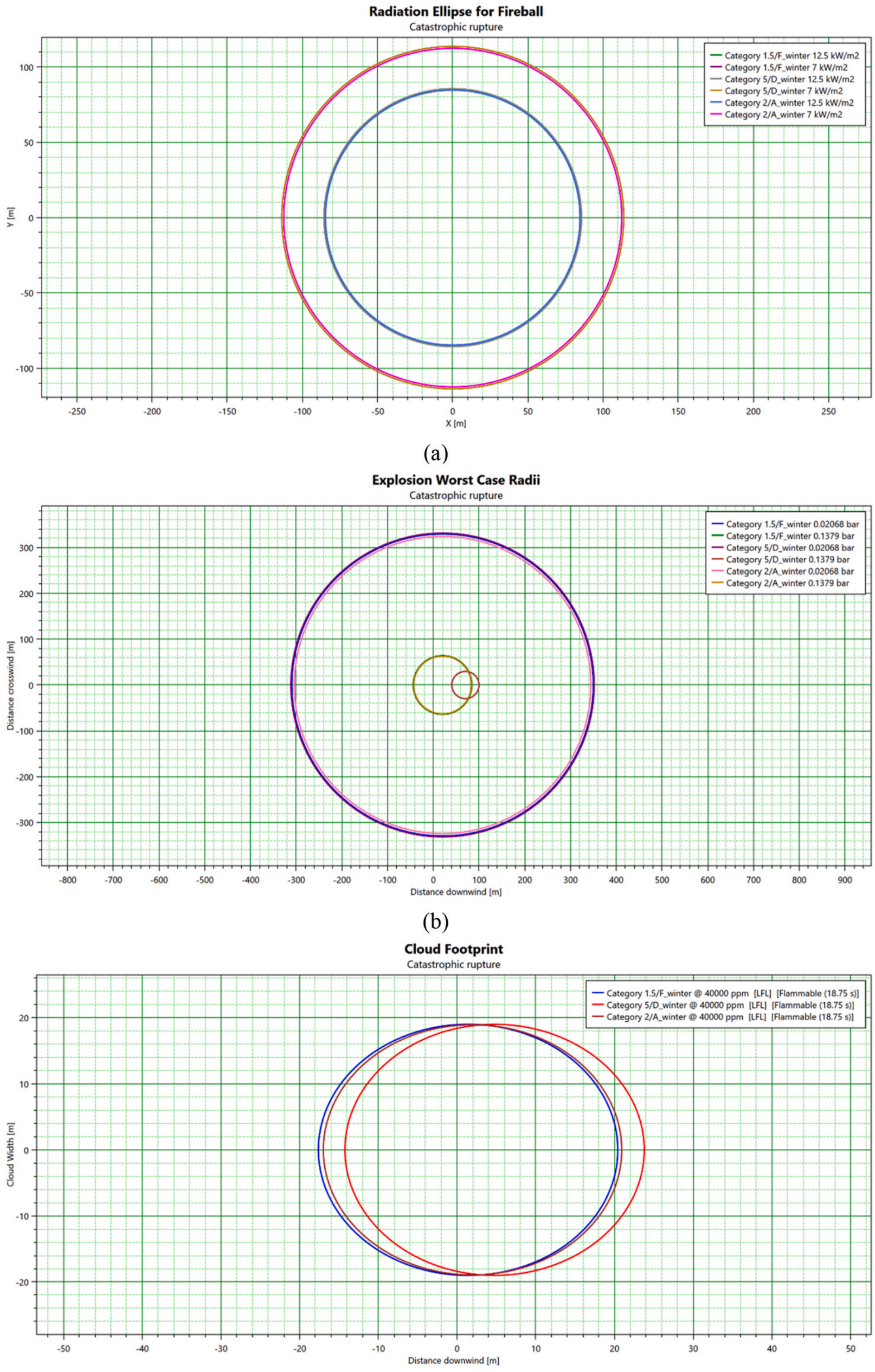
Before evaluating the risk, a further step for the event tree quantification is necessary to assign a probability of having a specific event. The event trees are available in Section S6 of the Supplementary Material, and the specific probabilities are assessed considering the release rate resulting from the Phast simulation and available in Table S.5-S.7 in the Supplementary Material.

Implementing the outcomes of the previous steps in Equations (1) and (2), it is possible to associate each component with the coordinate corresponding to the impact area. This value is the input for the x-coordinate of the risk plot. The y-coordinate is expressed by the sum of the probabilities of all the LOCs, as explained in Section 3. The associated risk is calculated through Equation (3).

5.5. Risk plot

Fig. 7 shows the results in a risk plot, where consequences and probabilities are on a logarithmic scale under two atmospheric conditions: Pasquill class F and wind speed of 1.5 m/s (Fig. 7a) and Pasquill class D and wind speed of 5 m/s (Fig. 7b). The colors delineate four risk zones: green indicates low risk, yellow medium risk, orange medium-high, and red high risk. The boundaries between these zones are represented by smooth gradients, reflecting gradual transitions. Within this framework, truck hoses and the electrolyzer systems emerge as the two most critical components, located in the high and medium-high risk region, respectively. The storage vessel and the electrolyzer line fall within the green-to-yellow transition zone, straddling low and medium risk. The 5 bar reduction line falls in this region only for the second environmental scenario considered (Fig. 7b). All remaining components lie in the low-risk area. The component most affected by atmospheric conditions is the line to the burner, although in both cases it remains in the low-risk zone. The iso-risk plot for the third case (Pasquill class A and wind speed of 2 m/s) is shown in the Supplementary Material and yields results similar to those of the first case. In all three cases, the air temperature and relative humidity have a negligible impact on the results. In general, more stable atmospheric conditions (e.g., Pasquill class F) are expected to provide more conservative outcomes in consequence analyses. However, in the present case, the effect of wind speed plays a more significant role. According to the adopted jet fire model (the Miller model [69], as recommended by DNV [70], higher wind speeds increase the predicted jet fire length and associated impact distances. Consequently, for components where the jet fire represents the dominant endpoint event, such as the line to the burner, an increase in wind speed results in a noticeable enlargement of the overall impact area, partially offsetting the expected conservativeness associated with more stable atmospheric conditions.

Among all, the truck hoses, the storage vessel, and the buffer tank exhibit the largest impact areas. Except for the first, the high hydrogen inventory is balanced by the very low probability of failure, resulting in a low associated risk. The piping network shows substantial variability in both the impact area and the probability of failure. It may appear counterintuitive that the high-pressure lines are associated with smaller consequences. However, operating conditions are not the only factors impacting this result. Specifically, the hydrogen content in 100 bar, 50 bar, and 30 bar reduction is lower because these pipes are shorter. Moreover, one of the release scenarios is defined based on a 10% diameter failure. As a result, a leak from a small diameter inherently involves a smaller orifice and thus a more minor release than the same percentage breach in a larger-diameter pipe, such as the 10 bar reduction pipe. Furthermore, the variability in probabilities is attributable to



(a)

(b)

(c)

Fig. 6. Example of results obtained from the Phast software: iso-intensity curves of a fireball (a), iso-overpressure curves of an explosion (b), iso-concentration curves of a flash fire (c).

differences in pipe diameter and length. According to the reference data used in this study [37], piping is classified into three diameter-based categories, with failure probability decreasing as diameter increases. Additionally, the base failure rate must be scaled by the total length of the pipe. Thus, in this study, a shorter pipe with a smaller diameter (e.g., 100 bar pipe) shows a comparable probability of failure to a longer pipe with a larger diameter (e.g., 10 bar pipe).

5.6. *Maintenance priority assessment*

The risk ranking highlights the truck hoses and the electrolyzer as critical components for maintenance prioritization. Since the electrolyzer system is composed of multiple individual components, the GeNIe Modeler software is used to perform a sensitivity analysis to understand which specific components need more attention. In addition,

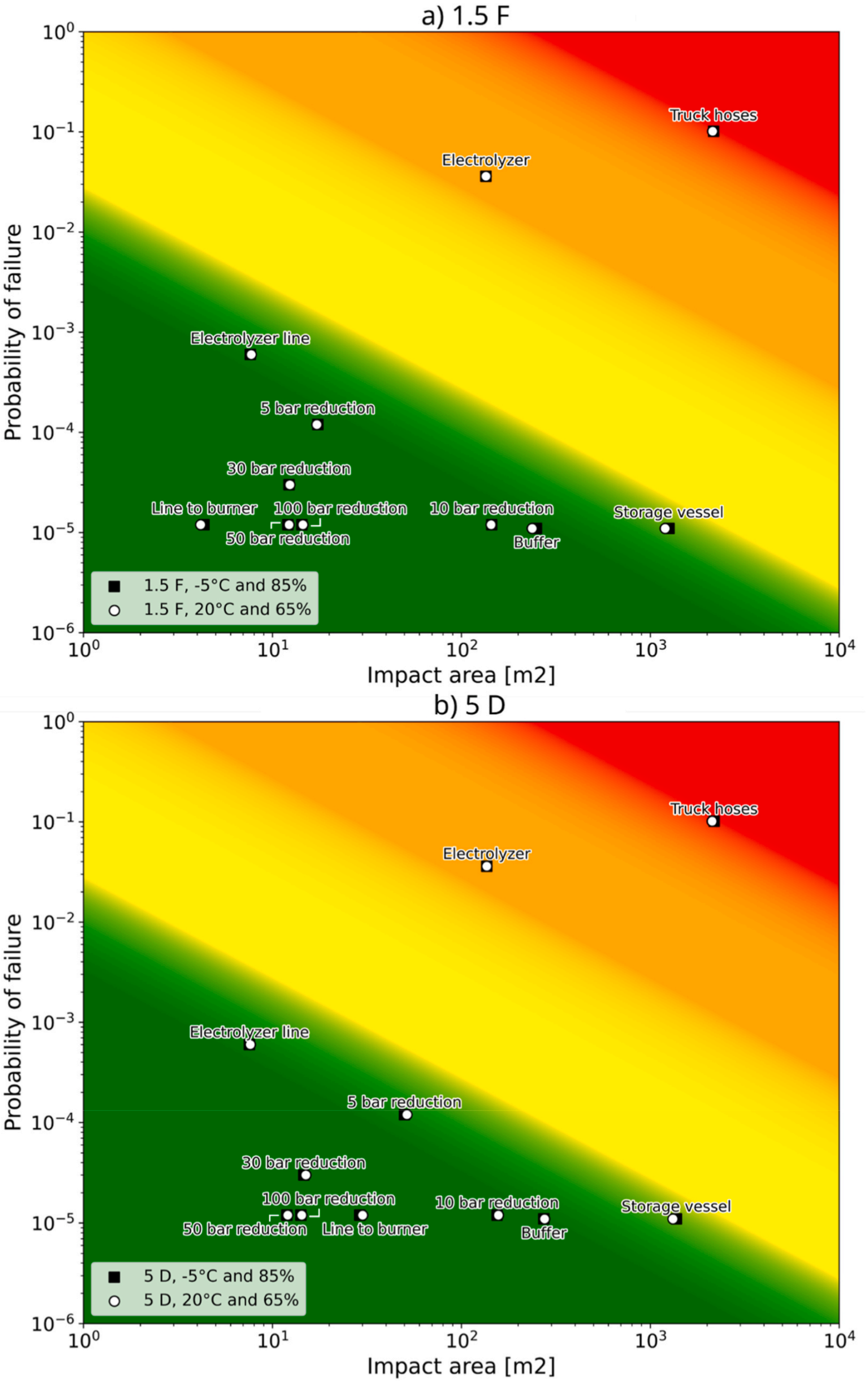


Fig. 7. Iso-risk plots for the hydrogen-fueled glass manufacturing in different environmental conditions: a) Pasquill class F and wind speed of 1.5 m/s; b) Pasquill class D and wind speed of 5 m/s.

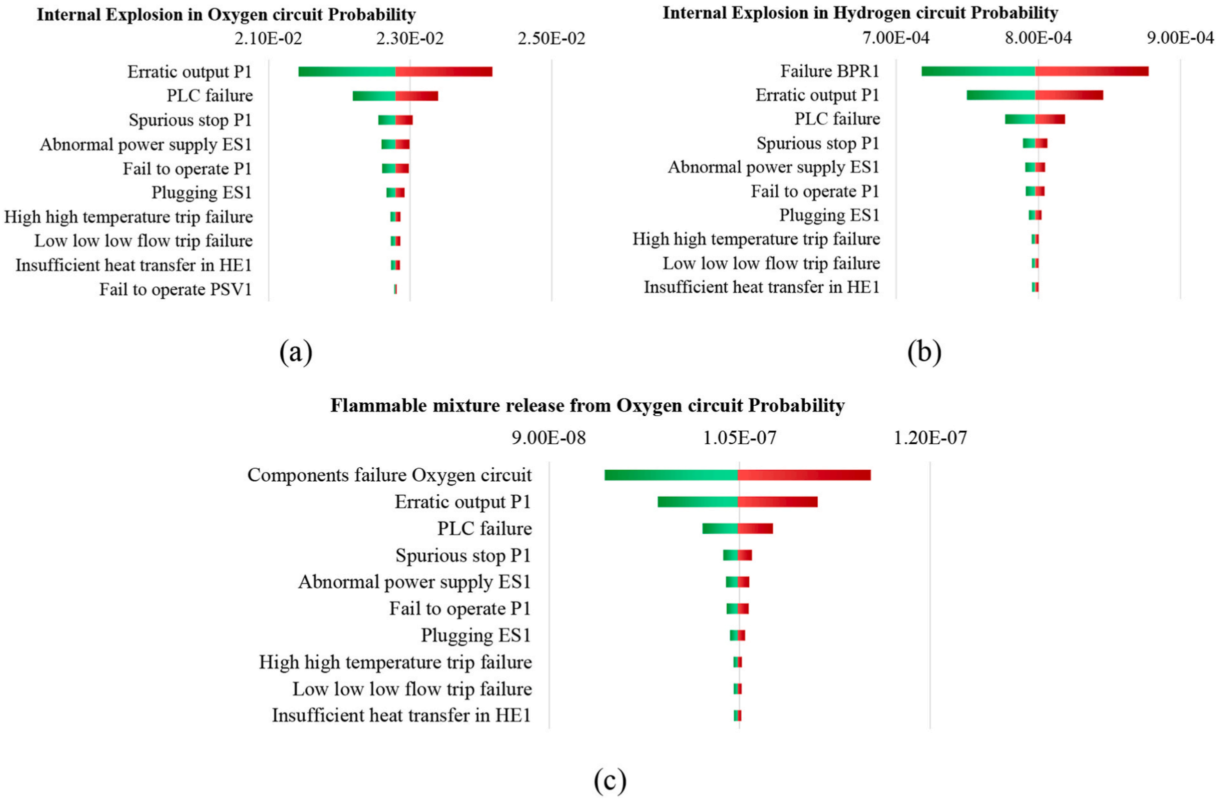
considering the uncertainty associated with the reliability data adopted in this study, the sensitivity analysis also provides an indication of the robustness of the results with respect to variations in the input probabilities. The tornado charts presented in Fig. 8 quantify the sensitivity of selected top-level events—namely, internal explosions in the oxygen (a) and hydrogen circuits (b), and flammable mixture release from the oxygen circuit (c)—to variations in the probability of basic events in the Bayesian Network. Pure hydrogen release scenarios were also considered in the overall risk assessment (see Table 6); however, they are not included in this sensitivity analysis because the associated fault tree (Figure S.1 in Supplementary Material) consists exclusively of OR gates representing leak events from different components. As a result, the top event probability is obtained by directly summing the basic event frequencies, assuming they are independent, which does not yield meaningful ranking information in tornado charts. Specifically, a 10% perturbation was applied to the prior probability of each basic event the resulting impact on the probability of the top event is calculated. GeNIe automatically ranks the basic events based on the magnitude of their influence, measured as the absolute change in the target node's probability. The horizontal bars in the charts represent this influence: red indicates a positive correlation (i.e., increasing the basic event probability raises the top event probability), while green represents a negative correlation. This method enables the identification of the most critical contributors to compromising the electrolyzer's safety. The basic events that primarily impact the internal explosion in the oxygen circuit are the failures associated with the water pump feeding the membrane (Erratic output P1, Spurious stop P1, and Fail to operate P1) and the PLC failure, responsible for the activation of the alarms. The failure of the back pressure regulator (BPR1) is the main contributor to the internal explosion in the hydrogen circuit. As mentioned before, this scenario requires not only membrane degradation that allows cross-flow, but also a simultaneous pressure reduction in the hydrogen side. Similarly, the release of a flammable mixture from the oxygen side strongly depends on the probability of leaks from components within that circuit (PO1, PO2, OWS1), as well as the presence of a flammable mixture. However, this scenario shows a much lower probability compared to the first two events.

6. Discussion

This work demonstrates that electrolyzer systems can be consistently integrated into the RBM framework by defining credible release scenarios and assigning occurrence probabilities. At the same time, the results provide a broader contribution, as the identified LOC can be applied in other safety domains (e.g., inherent safety studies or comprehensive QRA).

Building on this information, mapping the fault trees in a Bayesian network is particularly relevant in the context of electrolyzer systems, where technological evolution may introduce new components. Also, the configuration under analysis in Fig. 4 should be considered as a representative but non-exhaustive model. Although it captures the most common components in industrial electrolyzer setups, other configurations may feature additional or alternative elements depending on the specific technology or design.

Another relevant aspect concerns the scale of the electrolyzer system considered in this work. The system analyzed in this work represents an industrial-scale electrolyzer installation integrated into an operating industrial process. Compared with laboratory-scale systems previously analyzed in the literature, industrial installations involve more complex BoP configurations, including multiple stacks and additional control systems. This increased system complexity introduces additional failure modes and interactions between subsystems that must be explicitly considered in the risk modelling framework. In addition, the larger scale of industrial electrolyzer systems inherently involves increased



(a)

(b)

(c)

Fig. 8. Tornado charts obtained from the sensitivity analysis. A 10% variation of the basic event is imposed, and the impact on internal explosion in oxygen circuit probability (a), internal explosion in hydrogen circuit probability (b), and flammable mixture release from oxygen circuit probability (c) are reported. Only the 10 most influential basic events are shown.

equipment dimensions and higher hydrogen inventories compared with laboratory-scale installations. As a consequence, accidental releases occurring in industrial facilities may lead to significantly more severe consequences in terms of potential hazard distances. The results obtained in the present study for leakage scenarios involving the hydrogen separator highlight this effect, showing larger impact distances than those reported in the available literature for laboratory-scale electrolyzer systems [29]. These findings emphasize the importance of carefully addressing scale-related effects in safety assessments and risk management strategies for large-scale water electrolysis plants.

The current risk ranking, as represented in Fig. 7, is based on failure probabilities assumed to follow a constant failure rate distribution. These values do not account for time-dependent degradation and therefore represent a simplified, time-invariant approximation of real operational risk. In reality, most industrial components are subjected to progressive deterioration due to mechanisms such as corrosion, fatigue, thermal stress, and hydrogen embrittlement. As a result, the actual likelihood of failure often increases with time in-service, especially in systems exposed to high-pressure hydrogen environments. Incorporating time-dependent damage factors into the analysis would enable the development of a realistic and quantitative maintenance plan.

According to the preliminary methodology developed by Campari et al. [27], and assuming the same material for all the pipes, the damage factor accounting for hydrogen embrittlement increases with increasing pressure. Thus, it can be expected that the 100 bar pipe may require maintenance operations earlier than the 30 bar pipe, even though the latter is currently closer to the risk transition zone. Regarding pressure vessels, the influence of degradation is expected to be less significant. Campari et al. [10] shows much smaller damage factors for storage tanks, attributing only the liner degradation and assuming that these types of vessels (type IV) are not susceptible to hydrogen embrittlement. Additionally, considering that the plant is assumed to be newly constructed, it is reasonable to suppose that materials have been carefully selected to ensure full compatibility with hydrogen service. In this context, the material susceptibility factor is expected to be low. Consequently, hydrogen-induced degradation mechanisms are not anticipated to significantly affect the failure probabilities, in contrast to retrofitted hydrogen pipelines, where hydrogen-enhanced fatigue constitutes a major degradation mechanism [26,71].

The electrolyzer system presents more complex and less-known scenarios. In particular, the reliability data currently available for hydrogen technologies remains limited, and failure frequencies are often estimated using datasets originally developed for conventional process industries (e.g., oil and gas). While these datasets provide a reasonable proxy for generic balance-of-plant components, they may not fully capture hydrogen-specific degradation mechanisms such as membrane ageing or catalyst degradation in PEM electrolyzers. In this context, the sensitivity analysis discussed in Section 5.6 plays a key role in evaluating the robustness of the results with respect to uncertainty in the adopted failure data. Prioritizing the monitoring of electrolyzer components that have a higher impact on the probability of a hazardous scenario should be imperative. Developing specific monitoring strategies for electrolyzers would support a more dynamic risk management approach. By complementing current risk models with real-time operational data, researchers and operators can better understand how this system evolves and anticipate degradation trends before they lead to critical failures. In this regard, the development of a Bayesian network within the current methodology represents a significant advantage. This framework is inherently suited to incorporate new evidence as it becomes available, allowing for continuous model refinement. As monitoring data from electrolyzer operation accumulates, the network can dynamically update failure probabilities and risk estimates, thereby enhancing predictive capabilities and supporting evidence-based maintenance decisions.

7. Conclusions

The integration of hydrogen technologies into industrial sectors, particularly within hard-to-abate domains such as glass manufacturing, represents a fundamental shift toward achieving decarbonization goals. However, this transition involves not only technological adaptation but also the development of enhanced risk management and maintenance strategies. This study proposed and demonstrated an adapted RBM methodology specifically tailored to hydrogen systems, particularly in contexts involving on-site production via PEM electrolyzers.

The proposed framework is built upon and adapted from the conventional RBI methodology outlined in API 580 and API RP 581. While the API RBI framework provides a solid foundation for risk assessment in traditional oil and gas settings, it lacks coverage for hydrogen-related components and failure modes. This study integrated additional qualitative tools (FMEA, Fault Tree Analysis) and quantitative tools (Bayesian Networks, consequence modeling via PHAST software), enabling the identification of both conventional and emerging risks. This dual-level approach ensured that components not covered by standards, such as those within hydrogen-specific equipment, are systematically assessed.

From a theoretical perspective, this work has several contributions. First, it proposed a step toward the application of the RBM to hydrogen systems using a case study in the glass sector to highlight its practicality and relevance. Second, the analysis highlights how hydrogen-specific systems—such as PEM electrolyzers—introduce unique and critical failure modes that are not present in conventional systems. In particular, membrane degradation leading to the potential formation of an explosive hydrogen-oxygen mixture inside electrolyzer components, emerged as a significant risk scenario in terms of both likelihood and impact. Third, the integration of Bayesian Networks allowed for a concise representation of the electrolyzer's LOC events and for a sensitivity analysis, identifying the most influential basic events contributing to top-level failures. Such an approach becomes particularly relevant when analysing industrial-scale electrolyzer installations, where increased system complexity and multiple interacting subsystems introduce additional failure modes that must be captured in the model. This aspect is particularly useful for guiding monitoring priorities and enabling real-time updates of the risk model based on new evidence or operational data. Fourth, the study provided a comprehensive assessment of the consequences of an industrial-scale electrolyzer system. The analysis evaluates the potential impact of accidental releases associated with large-scale installations and extends the scope of current literature by explicitly considering the possible release of hydrogen–oxygen mixtures generated within the electrolyzer circuits.

From a practical perspective, the methodology can be applied by asset managers or maintenance managers to prioritize maintenance activities. The risk plot analysis offered a clear visualization of component criticality. Among all system components, truck delivery hoses and the electrolyzer system resulted in the medium-high risk zone, warranting enhanced maintenance attention. Other components, such as the high-pressure pipelines or storage vessels, despite containing large hydrogen inventories, showed lower risk profiles due to their low estimated failure probabilities.

As any other work, this study has limitations. The current reliability data are derived from the oil and gas database and may not fully capture the behavior of hydrogen technologies. Thus, future development can refine the available data to obtain more realistic results. This reinforces the importance of developing hydrogen-specific datasets and continuously updating probabilistic models through real-world monitoring. In this regard, the flexibility of the Bayesian framework and its ability to integrate new evidence stand out as essential features for the long-term success of risk-based maintenance strategies. Moreover, this work does not consider time-dependent degradation phenomena. Future works can include time-dependent factors to have more realistic outcomes. While the risk rankings provided a valuable snapshot, integrating degradation models would enable a more comprehensive prediction of failure over time, allowing for a transition from a qualitative ranking to a fully quantitative, predictive maintenance scheduling.

CRediT authorship contribution statement

Giulia Collina: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Marta Bucelli:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Leonardo Leoni:** Writing – review & editing, Writing – original draft, Visualization, Methodology. **Logan Martens:** Writing – review & editing. **Alessandro Tugnoli:** Writing – review & editing, Visualization, Supervision. **Nicola Paltrinieri:** Writing – review & editing, Supervision, Funding acquisition.

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.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2026.155318.

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