Article:

Hoseyni, S.M. orcid.org/0000-0001-7947-8223, Mesbah Mostafa, M.O. and Cordiner, J. orcid.org/0000-0002-9282-4175 (2024) Mitigating risks in hydrogen-powered transportation: A comprehensive risk assessment for hydrogen refuelling stations, vehicles, and garages. International Journal of Hydrogen Energy, 91. pp. 1025-1044. ISSN 0360-3199

https://doi.org/10.1016/j.ijhydene.2024.10.074

International Journal of Hydrogen Energy 91 (2024) 1025–1044

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

Mitigating risks in hydrogen-powered transportation: A comprehensive risk assessment for hydrogen refuelling stations, vehicles, and garages

Seyed Mojtaba Hoseyni, Mohamed Osman Mesbah Mostafa, Joan Cordiner *

School of Chemical, Materials and Biological Engineering, The University of Sheffield, Sir Robert Hadfield Building, Mappin Street, S1 3JD, Sheffield, UK

A R T I C L E I N F O

Handling Editor: Ramazan Solmaz

Keywords:
Hydrogen
Safety
Risk assessment
Structured what-if (SWIFT)
Bowtie barrier analysis
Transportation

A B S T R A C T

Hydrogen is increasingly seen as a viable alternative to fossil fuels in transportation, crucial to achieving net-zero energy goals. However, the rapid expansion of hydrogen-powered transportation is outpacing safety standards, posing significant risks due to limited operational experience, involvement of new actors and lack of targeted guidelines. This study addresses the urgent need for a tailored comprehensive risk assessment framework. Using Structured What-If (SWIFT) and bowtie barrier analysis, the research evaluates a hypothetical pilot project focusing on hydrogen refuelling stations, vehicles, and garages. The study identifies critical hazards and assesses the adequacy of current risk mitigation measures. Key findings reveal gaps in safety practices, leading to 41 actionable steps and 5 key activities to help new actors manage hydrogen risks effectively. By introducing novel safety guidelines, this research contributes to the development of safe hydrogen use and advances the understanding of hydrogen risks, ensuring its sustainable integration into transportation systems.

1. Introduction

Hydrogen shows an immense potential as a cleaner and sustainable alternative to traditional fossil fuels across a range of applications [1]. In order to ensure the utmost safety during its handling and utilization, a comprehensive understanding of hydrogen's properties is crucial. This versatile element exists in multiple forms and is commonly stored and transported either as a compressed gas, a cryogenic liquid, or in the form of chemical compounds [2]. However, hydrogen's unique properties give rise to safety-related issues. It is highly flammable, has a wide flammability range, and burns with an invisible flame, making leak detection and fire detection a challenging mission. The hazardous nature of hydrogen necessitates the implementation of robust safety measures to mitigate risks [3].

The use of hydrogen in transportation has gained significant momentum in the push toward a net-zero energy future, but ensuring its safety remains a major challenge. Many new participants entering this sector often lack the necessary knowledge and awareness of the specific risks associated with hydrogen. Furthermore, the sector suffers from limited operational experience and historical data to guide safe practices [4,5]. Compounding these issues, there are currently limited comprehensive standards or guidelines to enforce safety measures effectively [6]. As a result, addressing these gaps is crucial to mitigating risks and ensuring the safe and successful deployment of hydrogen technologies in transportation.

Effective risk assessment and mitigation strategies are essential to ensuring the safety of hydrogen refuelling stations. This was underscored by an accident at a hydrogen refuelling station in Sandvika, Norway, where an explosion and fire caused significant damage to the station's infrastructure and nearby vehicles. The incident highlights the critical need to address safety concerns in hydrogen applications [7]. Hydrogen-powered vehicles also present unique safety challenges. It is essential for system designers, regulators, and users to have a comprehensive understanding of the potential hazards and associated risks involved. Comparisons have been made between hydrogen and other fuels in terms of severity in case of a fuel leak and ignition, emphasizing the need for careful consideration of consequences [8]. Furthermore, a recent fire occurred at Golden Empire Transit in California in July 18, 2023, damaging a hydrogen fuel cell bus and raising concerns about the safety of hydrogen as a fuel source for public transportation. Although the aforementioned incidents could potentially cause unease and anxiety among the general public, it is crucial for implementing appropriate safety measures and mitigating risks effectively to promote the general individuals understanding on the safety implications of hydrogen in end-user applications. It is of utmost importance to tackle the integration of hydrogen technology with a comprehensive comprehension of

* Corresponding author.
E-mail address: j.cordiner@sheffield.ac.uk (J. Cordiner).

https://doi.org/10.1016/j.ijhydene.2024.10.074
Received 16 August 2024; Received in revised form 4 October 2024; Accepted 6 October 2024
Available online 19 October 2024

the obstacles and the continuous efforts to boost the safety and efficacy of this revolutionary system [9].

Ensuring the safe deployment of hydrogen as an energy source in transportation sector requires addressing its safety concerns in various end-user applications. This includes hydrogen-refuelling stations, vehicles, and repair garages [10]. Robust risk assessment techniques and design reviews play a crucial role to identify potential hazards, evaluate their consequences, quantify the uncertainties and develop effective mitigation strategies [11,12]. Numerous studies have been conducted to identify the hazards and assess the risks associated with deploying hydrogen as an alternative fuel in transportation. These studies mostly include detailed Quantitative Risk Assessments (QRA), accident modelling, and Computational Fluid Dynamics (CFD) simulations for Hydrogen Refuelling Stations (HRS), hydrogen-powered vehicles, and their parking or repair garages:

Nakayama et al. conducted a preliminary hazard identification and risk assessment for HRS alongside the conventional fuel stations [13]. Suzuki et al. used HAZOP to identify accident scenarios in HRS [14]. Wang & Gao conducted a DBN-based risk assessment of hydrogen leakage risk in refuelling stations [15]. Park et al. investigated the potential individual and societal hazards posed by HRS in urban settings [16]. By simulating accidents and using event trees and fault tress, Al-Shanini et al. examined the safety of a hydrogen station [17]. Gye et al. carried out a QRA of a high-pressure hydrogen refuelling station situated in a densely populated urban [18]. Zhiyong et al. conducted a QRA on a station in Shanghai [19]. Yoo et al. compared the risks of liquefied and gaseous hydrogen refuelling stations [20]. Tsunemi et al. performed a QRA of human safety during the operation of a HRS [21]. There are some other researches which have recently conducted QRA for HRS [22–31].

Regarding the safety of hydrogen-powered vehicles, Rodionov et al. conducted one of the first risk assesment studies on cars with hydrogen-driven engines [32]. Shen et al. conducted a HAZOP and FMEA study for preliminary hazard identification of hydrogen fuel cell vehicles (HFCVs) [33]. Ehrhart et al. assessed the risk of HFCVs accidents in tunnels [34]. Al-Douri et al. carried out a QRA analysis for hydrogen fuel cell forklifts by employing FMEA and fault trees [35]. Spada et al. conducted a cpmaritive risk assessment study for different hydrogen fuel cell types in EU [36]. Cui et al. analysed the risk of fire and leakage explosion in HFCVs by FMEA and risk matrix [37]. The QRA for road accidents of HFCVS is conducted by Sun & Li [38]. There are some recent researches assessing the leakage risk in HFCVs using CFD simulation [39–42]. CFD simulation is also used to model the consequences of hydrogen leakage and explosion in parking garages [43–45]. Ehrhart et al. carried out ventilation modelling and HAZOP for hydrogen release in repair garages [46].

The available literature predominantly focuses on specific accident scenarios, providing quantitative risk assessments for these isolated cases. Although numerous simulations and CFD models exist for refuelling stations, vehicles, and parking garages, their results are often not applicable, comprehensible, or practical for end-users and new actors. This reveals a significant gap in applicable references for the hydrogen deployment within the net-zero energy transition, where safety is paramount. This challenge is further compounded by the lack of targeted research and guidelines, making it increasingly difficult for new actors and end-users to safely adopt and promote the widespread use of hydrogen.

This paper focuses on mitigating risks in hydrogen-powered transportation, addressing a critical gap identified in existing literature. Unlike previous studies that are limited to specific accident scenarios and often lack applicability for end-users and new actors, this research takes a novel approach by applying two specific risk assessment techniques: The Structured What-If (SWIFT) method and Bowtie Barrier analysis are employed to assess a hypothetical pilot project for a country embarking on its first hydrogen transportation initiative. These methods were selected to create a comprehensive risk assessment process where concluded results are tailored to non-experts, including officials and the new actors in hydrogen-powered transportation. Specifically, the methodology is demonstrated in a case study that focuses on a pilot project deploying a hydrogen-powered transportation system, with risk assessments conducted on the hydrogen refuelling stations, vehicles, and parking garages. The findings are translated into actionable recommendations designed to effectively manage inherent risks. By making safety information more accessible and understandable, this project contributes to the safe and widespread adoption of hydrogen in the net-zero energy transition.

The remainder of this paper is organized as follows: Section 2 introduces the methodology for SWIFT and Bowtie barrier analysis. Section 3 outlines a pilot project for deploying hydrogen infrastructure within a country. This includes the establishment of hydrogen refuelling stations, the integration of hydrogen-powered vehicles, and the adaptation of garages. The section provides a comprehensive risk assessment for these components. Section 4 discusses the results and provides applicable actions that can be used to mitigate risks. Section 5 conclude the paper with some remarks.

2. Methodology

In this work, the SWIFT and Bowtie Barrier Analysis risk assessment methodologies are used to provide a clear and easily understandable overview of this novel application, its associated risks, and the strategies that governments, companies, and individuals will use to manage them. In this section, these methodologies will be elaborated upon in more details.

2.1. SWIFT

A commonly employed method is the SWIFT technique, known for its flexibility in identifying risks, particularly at a higher level. It can function independently or as a component of a staged approach, contributing to the overall efficiency of other methods [47].

SWIFT employs organized brainstorming within a guided workshop environment. In this setting, a predefined list of guiding terms is integrated with input from participants, frequently initiated by expressions like “what if?” or “how could?”. This approach bears a resemblance to HAZOP, but it focuses on assessing a system or subsystem rather than examining the original designer’s intentions.

Prior to commencing the study, the facilitator compiles a list of prompts to facilitate a thorough examination of risks or potential sources of risk. At the onset of the workshop, there is a discussion regarding the context, scope, and objectives of the SWIFT process and specific criteria for success are clearly defined. Utilizing the guiding terms and “what if?” prompts, the facilitator invites participants to bring up and deliberate upon various issues, including but not limited to:

- Risks that are already identified.
- The origins and factors driving these risks.
- Past experiences, both successful and problematic.
- Existing safety measures and their effectiveness.
- Relevant rules and limitations imposed by regulations.

The facilitator relies on the prompt list to oversee the conversation and to propose additional topics and situations for the team to consider. The team evaluates whether the existing safety measures are sufficient and, if not, explores possible solutions. Throughout this discussion, they continue to pose additional “what if?” questions.

In certain scenarios, particular risks are pinpointed, and a detailed account of the risk, including its origins, potential outcomes, and preventive measures, may be documented. Furthermore, broader origins of risk, issues with control measures, or systemic challenges might also become known.

When a list of risks is compiled, a qualitative or semi-quantitative risk assessment method is frequently employed to prioritize the actions based on their perceived level of risk. This assessment typically considers the effectiveness of the current control measures in place. Table 1 describes the SWIFT characteristics as per Risk management – Risk assessment techniques standard [48]:

The SWIFT technique is strongly applicable for risk identification and applicable for risk analysis and risk evaluation according to ISO 31000-risk management process [48].

2.1.1. Usage

This technique is versatile and can be applied to a wide range of elements, including systems, equipment, procedures, and entire organizations. Its primary purpose is to examine the effects of modifications and study how they could affect the associated risks. Additionally, it serves the purpose of identifying issues where it would be worth to allocate resources for a more comprehensive examination using other detailed techniques.

2.1.2. Inputs

To effectively use SWIFT, it is crucial to have a good understanding of the system, process, equipment, or changes involved, along with the external and internal factors that influence them. This understanding is established by talking to people, assembling a diverse team, and reviewing documents, plans, and drawings.

Usually, the system being studied is broken down into smaller parts to make it easier to analyse. While the facilitator needs training in using SWIFT, it is a skill that can typically be learned relatively quickly.

2.1.3. Outputs

The results of this process encompass a record of identified risks, each ranked based on its level of importance, along with corresponding actions or tasks. These risk-ranked actions then serve as the foundational elements upon which a comprehensive management plan can be developed.

2.1.4. Strengths and limitations

SWIFT is a versatile and efficient risk assessment method applicable across various domains, requiring minimal preparation and quickly identifying major risks and system responses to deviations. It excels in pinpointing areas for process and system improvement, reinforcing accountability, and generating comprehensive risk documentation with ease. However, its effectiveness is dependent on the team's experience and the quality of prompts, and it may overlook complex risks when applied at a high level, often resulting in generic recommendations that require further detailed analysis.

To address these inherent limitations, it may be advisable to employ an additional risk assessment technique, if deemed necessary, following the completion of the SWIFT process. This supplementary approach can serve as a valuable means to further enhance the comprehensiveness and depth of the risk assessment, compensating for any potential gaps or constraints encountered during the SWIFT analysis.

2.2. Bowtie barrier analysis

The Bowtie barrier analysis technique provides a graphical depiction of potential hazards, their underlying causes, as well as the preventive and mitigation barriers that should be implemented [49].

The bowtie methodology is developed through the following sequence:

1. Hazard Identification;
2. Top event Determination (if the control over the hazard is lost);
3. The undesirable consequences identification;
4. Identification of potential threats that may lead to the top event;
5. Identification of prevention barriers to avert the occurrence of the top event due to each threat;
6. Identification of mitigation barriers to alleviate the undesirable consequences;
7. Identification of degradation factors that could lessen the effectiveness of prevention and mitigation barriers;
8. Identification of degradation controls aimed at eliminating or minimizing the impact of the degradation factors

Fig. 1 below illustrates the core components of the bowtie methodology:

2.2.1. Usage

Table 2 describes the Bowtie characteristics as per Risk management – Risk assessment techniques standard [48]:

The Bowtie technique is applicable for risk identification, risk analysis and risk evaluation according to ISO 31000-risk management process [48].

2.2.2. Input

The input for this process encompasses vital information pertaining to the underlying threats and potential consequences associated with the pre-defined event, as well as any existing barriers that have the capacity to influence it. This valuable data can be sourced from various channels, including the results of risk and control identification techniques such as Hazard Identification (HAZID) and SWIFT or the insights derived from the first-hand experiences of individuals involved in the domain.

2.2.3. Output

The resulting output of this process appears in the form of a straightforward diagram. This diagram effectively illustrates the primary risk pathways, the currently implemented prevention barriers, and the degradation factors that could potentially contribute to barrier failures. Furthermore, it provides insights into the potential consequences of the identified risks and mitigation barriers that can be enacted in the aftermath of an event to mitigate these consequences.

2.2.4. Barrier types

After identifying the necessary barriers for preventing accidents or mitigating their consequences, it is essential to classify each barrier into categories that provide a clear understanding of each barrier's role and reliability within the system. The classifying barrier types are: passive hardware, active hardware, human intervention, and continuous hardware. Classifying barriers helps optimize safety design by balancing the use of different types, simplifying risk assessments, and improving decision-making on where to invest resources to enhance safety. It also supports compliance with industry safety standards and regulations.

Table 3 provides definitions for each barrier type and their corresponding colour codes, which will be used to distinguish the barrier types in the bowtie diagrams as wells as some examples for each barrier

Table 1
SWIFT characteristics [48].

Technique	Description	Application	Scope	Decision level	Starting info/ data needs	Specialist expertise	Qual/quant/ semi-quant	Effort to apply
SWIFT	A simpler form of HAZOP with prompts of "what if" to identify deviations from the expected.	Identify Risks	Organization and project level.	Strategic/ tactical.	medium	Low/ moderate	Qualitative	Low/ medium

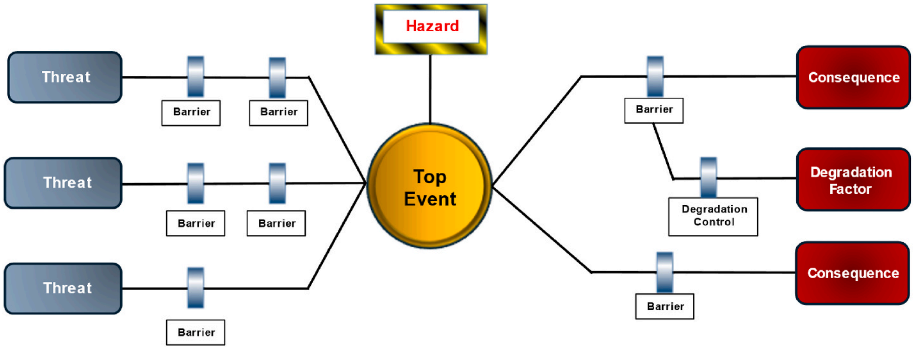

Fig. 1. Bowtie diagram template.

Table 2
Bowtie Characteristics [48].

Technique	Description	Application	Scope	Decision level	Starting info/data needs	Specialist expertise	Qual/quant/ semi-quant	Effort to apply
Bowtie	A diagrammatic way of describing the pathways from sources of risk to outcomes and of reviewing controls.	Analyse risk, analyse controls, describe risk	Project and Process/ equipment level.	Any	Low	Low/ moderate	Qualitative/Semi quantitative	Low

Table 3
Types of Barrier.

Short Name	Barrier Type	Description	Examples	Colour Code
Passive	Passive Hardware	The barrier works by virtue of its presence.	Dike, blast wall, crash barrier, anti-corrosion paint	
Active	Active Hardware	All elements of the barrier are executed by technology.	Process control systems and Safety Instrumented Systems	
Human	Active Hardware + Human Intervention	The barrier is a combination of human behaviour and technological execution.	Operator activated ESD valve Gas alarm and decision by human to evacuate	
	Active Human Intervention (predominantly human)	The barrier consists of human actions, often interacting with technology.	Operator detection and response (e.g., during structured walk around)	
Continuous	Continuous Hardware	The barrier is always operating.	Ventilation system, impressed current cathodic protection	

type:

2.2.5. *Strengths and limitations*

Bow tie analysis boasts several notable strengths:

- Clarity and Simplicity: It offers a straightforward and easily comprehensible visual representation of an event, its causes, and its potential consequences.
- Control Focus: Bow tie analysis directs attention towards existing control measures and evaluates their effectiveness in managing risks.
- Versatility: It can be applied not only to undesirable outcomes but also to desirable ones, making it a versatile tool.
- Accessibility: Bow tie analysis does not demand a high degree of expertise to be effectively utilized.

Bow tie analysis exhibits certain limitations, which are as follows:

- Inability to Represent Non-Independent Pathways: One of its constraints lies in its inability to describe scenarios where pathways from causes to the event are not independent, similar to the existence of logical “AND gates” in a fault tree analysis.
- Risk of Oversimplification in Complexity: Bow tie analysis may tend to oversimplify intricate situations, particularly when attempts are made to quantify risk. This oversimplification can potentially mask the complexities of the scenario, possibly leading to less precise risk assessments

2.3. Reflection of methodology in hydrogen-powered transportation

The clarity and simplicity of bowtie analysis make it highly effective in visually mapping potential risks and control measures associated with hydrogen refuelling stations, vehicles, and repair garages. Its strength lies in providing a straightforward overview of key risks and their corresponding barriers. However, its limitations become evident when assessing more complex, interdependent risks in hydrogen-powered transportation, such as simultaneous system failures or human-machine interactions. The method's inability to represent non-independent pathways and the potential for oversimplification can obscure critical risk factors in such scenarios.

Similarly, SWIFT has proven valuable for quickly identifying major risks and highlighting areas for improvement in hydrogen systems. However, its effectiveness is closely tied to the expertise of the assessment team. This reliance can lead to overly generic recommendations, particularly when applied at a high level, necessitating more detailed follow-up analyses to capture the full scope of risks involved.

Despite these limitations, the methodology employed in this study serves as a strong foundation for a pilot project, especially given the absence of well-established guidelines for hydrogen transportation and the urgency to meet net-zero targets. It offers a practical starting point to address immediate safety concerns, but for long-term success and enhanced safety, a more comprehensive risk assessment is required. Integrating additional methods such as Quantitative Risk Assessment (QRA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and consequence modelling will enable a more thorough examination of complex risk pathways and interactions inherent in hydrogen-powered systems.

Moreover, the development of specific regulatory standards and targeted guidelines is essential to ensure the safe and reliable deployment of hydrogen in transportation. Such regulations will not only fill the current gaps in safety protocols but also provide a framework for more rigorous risk assessments, ultimately fostering safer hydrogen-powered transportation systems.

3. The case study

In this work, we examine a hypothetical pilot project for a country embarking on its first attempt to integrate hydrogen into transportation.

The initial stage of the project will encompass the following key establishments:

- Production of fuel cell electric vehicles through one of the country's well-established manufacturers of traditional fossil fuel-based vehicles.
- Installation of 20 fixed hydrogen-refuelling stations in the capital city, strategically positioned to facilitate convenient access for hydrogen-powered vehicles.
- Preparation of five maintenance and service workshops, ensuring seamless functioning and upkeep of the hydrogen-based vehicles and refuelling stations.

Fig. 2 displays the project area of focus:

Hydrogen will be supplied by trucks from an existing refinery, with each refuelling station equipped with adequate storage facilities. The country lacks regulations for hydrogen use in vehicles or the construction of hydrogen-refuelling stations, though it does have regulations for traditional refuelling stations. A globally recognized contractor has been engaged to design, construct, and operate the hydrogen stations, as well as develop future guidance for legal compliance.

During the conceptual design phase, we opted to employ straightforward yet informative risk assessment methodologies to identify potential risks associated with the construction of the refuelling station, design aspects, operation, and maintenance of hydrogen vehicles, as well as the maintenance workshops. These methodologies serve the purpose of screening significant concerns, which we will then examine further during the detailed design phase. Additionally, this approach aims to enhance the understanding and awareness of client representatives, including officials and engineers involved in the project.

3.1. Hydrogen Refuelling Station (HRS)

Gaseous hydrogen will be transported to the refuelling stations using tube trailers. Subsequently, it will undergo compression and be stored within a buffer tank at the specified delivery pressure. The consumption of hydrogen will occur via dispensers, which draw hydrogen from the buffer tank through a regulator and cooler.

Fig. 3 provides a simplified diagram for the gaseous hydrogen refuelling stations. The station comprises hydrogen compressor, buffer tank, gas pressure regulator and the dispenser.

3.1.1. Preliminary hazard identification using SWIFT

During the HRS SWIFT workshop, a range of significant concerns were raised for discussion. These concerns included:

- Site Siting;
- Material of Construction;
- Staff Competence;
- The Maintenance Program;
- Material Aging;
- Vehicle Drivers Behaviour;
- Accidental Releases.

For each of these concerns, the underlying reasons behind the issues were explored and potential consequences that might arise if these concerns were not adequately addressed were also examined. Finally, recommendations were proposed with the aim of mitigating the associated risks. Table 4 shows the hydrogen refuelling station SWIFT Worksheet:

Fig. 2. Project area of focus.

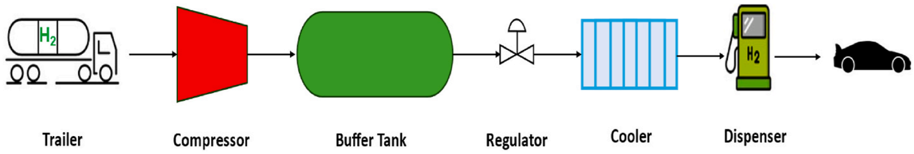

Fig. 3. Simplified Drawing for the hydrogen refuelling station main components.

It is worth mentioning that lack of knowledge/experience appears multiple times in Table 4 under reasons of concern. However, this lack of knowledge can often stem from a broader issue which is the absence of proper, systematic research that addresses these gaps. In emerging fields like hydrogen-powered transportation, the lack of comprehensive research is a significant concern, as it leads to gaps in data, case studies, and established methodologies. While individual expertise is important, the absence of systematic research limits the depth of understanding needed to identify potential risks and develop effective mitigation strategies. This can result in incomplete risk assessments, over-reliance on assumptions, and the use of outdated or contextually irrelevant data.

3.1.2. Bowtie barrier analysis

In the context of the HRS, the accidental release of hydrogen, which had been previously identified in the SWIFT analysis, was chosen as a top event for analysis within the bowtie barrier framework.

Subsequently, the next step involved the identification of potential undesirable outcomes resulting from this release scenario. In this instance, two distinct outcomes were identified:

- Fatalities/Injuries due to Hydrogen Fire/Explosion
- Severe Asset Damage due to Hydrogen Fire/Explosion

Following the identification of these outcomes, a series of issues were pinpointed as potential threats that could lead to the hydrogen loss of primary containment.

These issues encompassed the following:

- Hydrogen Compressor Mechanical Seal Failure
- Blocked Outlet in the Hydrogen Compressor Discharge
- Hydrogen Overpressure in the Storage Tank
- Storage Tank Corrosion
- Human Error during Refuelling
- Premature Opening of Pressure Safety Devices
- Failure of a Weak Joint
- Loss of Mechanical Integrity of Any Component
- Vehicle Collision/Crash
- Poor Vehicle Conditions

Subsequently, efforts were directed towards the allocation of expected barriers capable of either preventing the hydrogen release or mitigating the consequences if it were to occur. Additionally, any degradation factors that could compromise the effectiveness of these barriers were identified, and recommended actions or activities were proposed to ensure the continued functionality of these safeguards.

Figs. 4 and 5 display the barrier analysis for the hydrogen refuelling station:

Bowtie diagrams use a colour code to differentiate barrier types, as detailed in Table 3. For instance, in Fig. 4, the "High Pressure Trip" is represented as an active hardware barrier, color-coded in cyan. Additionally, the numbered labels attached to the barriers indicate the action code, which ensures the barrier's effectiveness by either confirming its strength or mitigating degradation factors. Table 5 includes all recommended actions associated with the bowtie barrier analysis.

There is a connection with the list of actions provided in Table 5 with the bowtie diagrams. As an example, in Fig. 4 (top left of the bowtie diagram), the threat of a hydrogen compressor mechanical seal failure is shown, which could potentially lead to hydrogen release in the HRS. Proper material selection is identified as a safety barrier to prevent the threat from triggering an accident. The action (shown with code 1 in Table 5 and labelled in Fig. 4) ensures that the equipment is designed according to the latest globally recognized codes and standards. Following these updated standards is crucial for ensuring safety, efficiency, and compliance, while also demonstrating adherence to industry best practices. A total of 17 actions were derived from the bowtie analysis. Due to word limitations, we have not provided detailed explanations for each action, but all are listed in Table 5.

Table 6 comprise all activities that were recommended in the HRS Bowtie Barrier Analysis:

3.2. Hydrogen vehicles

As a result of the current infrastructure deficiency (absence of hydrogen refuelling stations beyond the capital city), a decision was made to manufacture hydrogen hybrid vehicles, which integrate hydrogen fuel cell technology with a conventional gasoline or diesel engine. These vehicles employ the fuel cell system to generate electricity, propelling an electric motor, with supplementary power supplied by the internal combustion engine as required.

The following components constitute the proposed hydrogen hybrid vehicle:

- A hydrogen fuel cell responsible for converting hydrogen gas (H_2) and oxygen (O_2) from the air into electrical energy through an oxygen reduction reaction process.
- A hydrogen cylinder designed to store the compressed hydrogen gas required for the fuel cell system.
- An electric motor powered by the electricity generated from the fuel cell, serving to propel the wheels and deliver the necessary acceleration.
- A power control unit (PCU) responsible for providing proper power distribution. This unit manages the flow of electricity between the fuel cell system and the electric motor.
- A supplementary battery system acting as an energy buffer, capable of storing excess electricity generated by the fuel cell and releasing it when necessary.
- The conventional gasoline storage and combustion engine system.

3.2.1. Preliminary hazard identification using SWIFT

During the SWIFT workshop, a range of significant concerns were raised for discussion. These concerns included:

- Design;
- The Maintenance Program;
- Vehicle Aging;
- Vehicle Drivers Behaviour;
- Accidental Releases;
- Crash/Collision;
- Deliberate Acts.

For each of these concerns, the underlying reasons behind the issues were explored and potential consequences that might arise if these concerns were not adequately addressed were also examined. Finally,

Table 4
HRS SWIFT worksheet.

What if?	Reason of Concern	Potential Consequences	Recommendations
1.1 Improper station siting	1.1.1 Lack of knowledge/ guidance could lead to locating the hydrogen refuelling stations in congested locations	1.1.1.1 Potential of hydrogen fire/ explosion that could lead to multiple fatalities and severe property damage. This could also result in extended disruption to nearby infrastructure, traffic flow, and emergency services access.	1.1.1.1.1 Develop clear and comprehensive instructions for the design, installation, operation, and maintenance that must be strictly followed to obtain the operating license for the refuelling station.
		1.1.1.2 Difficulties in emergency response. This may lead to delays in managing hazardous situations, escalating risks.	1.1.1.1.2 Before proceeding with the proposed refuelling station, seek prior approval for the chosen location. The station operator must demonstrate their ability to run the facility safely through a meticulously crafted safety report. This report should include a detailed description of the location, station layout, equipment, design, operating conditions, staff competency, and an assessment of expected risks. Additionally, outline effective risk control measures to maintain risks at broadly acceptable levels or As Low As Reasonably Practicable (ALARP) levels. 1.1.1.1.3 During the design phase, well before construction, develop, review, and gain approval for the Emergency Response Plan (ERP) from authorized parties and legal authorities. The ERP must contain comprehensive emergency procedures, contact information, staff training requirements, communication protocols, and provisions for essential emergency equipment. Preparedness for unforeseen situations is crucial. 1.1.1.1.4 Assure that the civil defence and any emergency response parties can have more than two secure access to the HRS 1.1.1.1.5 During the project initial stages, select locations at the boundaries of the city and away from known congested locations.
1.2 Inadequate material of construction (structure, piping, connections, fittings, equipment)	1.2.1 Poor material selection. This may occur due to a lack of understanding of material properties, failure to adhere to standards, or cost-cutting measures that compromise safety. 1.2.2 Lack of knowledge/ guidance	1.2.1.1 Potential of hydrogen releases that could lead to fire/ explosion with potential fatalities and property damage. Failures could also lead to downtime and costly repairs, affecting station operations.	1.2.1.1.1 Refer to 1.1.1.1.1
1.3 Inadequate competence of station workers	1.3.1 Lack of knowledge/ experience	1.3.1.1 Potential for human errors that could lead to hydrogen releases. Such errors could escalate if proper emergency procedures are not followed, increasing the risk of severe accidents.	1.3.1.1.1 Personnel that are initially operating the HRS should have previous experience with similar stations or at least received a comprehensive training and passed qualification assessments before being in charge. 1.3.1.1.2 Comprehensive training and competence assessment programs are required for personnel operating hydrogen-refuelling stations.
1.4 Inadequate maintenance programs	1.4.1 Lack of knowledge/ guidance	1.4.1.1 Degradation of the HRS equipment that could lead to hydrogen releases with potential fire/explosion. This could also result in undetected wear or malfunction in critical systems, leading to higher long-term maintenance costs, increased risk of equipment failure, and extended operational downtime, which may impact the	1.4.1.1.1 Create clear and detailed instructions for the design, installation, operation and maintenance of that must be followed in order to provide the station owner with a license to operate.

(*continued on next page*)

Table 4 (*continued*)

What if?	Reason of Concern	Potential Consequences	Recommendations
		safety and reliability of the station.	
1.5 Inadequate competence of maintenance technicians	1.5.1 Lack of knowledge regarding HRS safety systems	1.5.1.1 Poor maintenance could lead to disabling safety system or inability to fix unknown defects. This could result in prolonged equipment failure, increasing the risk of hydrogen leaks or system malfunctions, with the potential for fire, explosion, and injury. Additionally, unaddressed defects may compromise future maintenance efforts.	1.5.1.1.1 Personnel maintaining the HRS should have previous experience with similar stations 1.5.1.1.2 Refer to 1.3.1.1.2
1.6 Aging of material	1.6.1 Material Deterioration due to wear/tear and other damage mechanisms. Failure to implement proactive material management and replacement strategies may exacerbate aging issues.	1.6.1.1 Sudden and repeated failure in critical components could occur. This could result in hydrogen release and fire with potential for fatalities and asset damage. Material degradation could also lead to higher maintenance costs, extended downtime, and decreased station reliability.	1.6.1.1.1 Assure the adequacy of the maintenance and inspection programs 1.6.1.1.2 Secure the required spare parts for safety critical equipment and replace them before the end of their end of life or in case of discovering unacceptable damage.
1.7 Accidental releases and/or fire	1.7.1 Many threats could lead to loss of containment such as mechanical damage, structure failure, human error, external fire, deliberate acts, etc.	1.7.1.1 Accidental hydrogen releases could lead to fire/explosion that could result in fatalities and property damage. Such incidents could lead to negative public perception, causing reputational damage to the facility operator.	1.7.1.1.1 Assure the presence of emergency shutdown switches in accessible locations for prompt response. 1.7.1.1.2 Assure the presence and effectiveness of the fire and gas detection, fire-fighting equipment. 1.7.1.1.3 Minimize the presence of ignition sources such as non-classified electrical equipment, smoking, hot work activities, etc. 1.7.1.1.4 During the design phase, well before construction, develop, review, and gain approval for the Emergency Response Plan (ERP) from authorized parties and legal authorities. The ERP must contain comprehensive emergency procedures, contact information, staff training requirements, communication protocols, and provisions for essential emergency equipment. Preparedness for unforeseen situations is crucial.
1.8 Poor behaviour of vehicle drivers	1.8.1 Lack of risk perception	1.8.1.1 Poor behaviour of individuals could lead to accidental release of hydrogen and fire. Failure to control driver behaviour could also increase the likelihood of accidents in high-traffic areas, exacerbating the overall risk.	1.8.1.1.1 Assure the presence of warning signs and alarms, and CCTV system. 1.8.1.1.2 Assure the design of the dispensing system is inherently safe and considers the probability of human failure. 1.8.1.1.3 Refer to 1.7.1.1.3

recommendations were proposed with the aim of mitigating the associated risks.

Table 7 shows the Hydrogen Vehicle SWIFT Worksheet:

3.2.2. Bowtie barrier analysis

In the context of the Hydrogen vehicle, the accidental release of hydrogen, which had been previously identified in the SWIFT analysis, was chosen as a top event for analysis within the bowtie barrier framework.

Subsequently, the next step involved the identification of potential undesirable outcomes resulting from this release scenario. In this instance, fatalities/Injuries due to Hydrogen Fire/Explosion was selected as the major undesirable outcome. Following the identification of these outcomes, a series of issues were pinpointed as potential threats that could lead to the hydrogen loss of primary containment.

These issues encompassed the following:

- Hydrogen pressure build up;
- Vehicle Collision/Crash;
- Failure of a Weak Joint;
- Loss of Mechanical Integrity of Any Component;
- Fuel cell thermal runaway reaction;
- Premature Opening of Pressure Safety Devices;
- Human Error during Refuelling;
- Poor Vehicle Conditions.

Subsequently, efforts were directed towards the allocation of expected barriers capable of either preventing the hydrogen release or mitigating the consequences if it were to occur. Additionally, any degradation factors that could compromise the effectiveness of these barriers were identified, and recommended actions or activities were proposed to ensure the continued functionality of these safeguards.

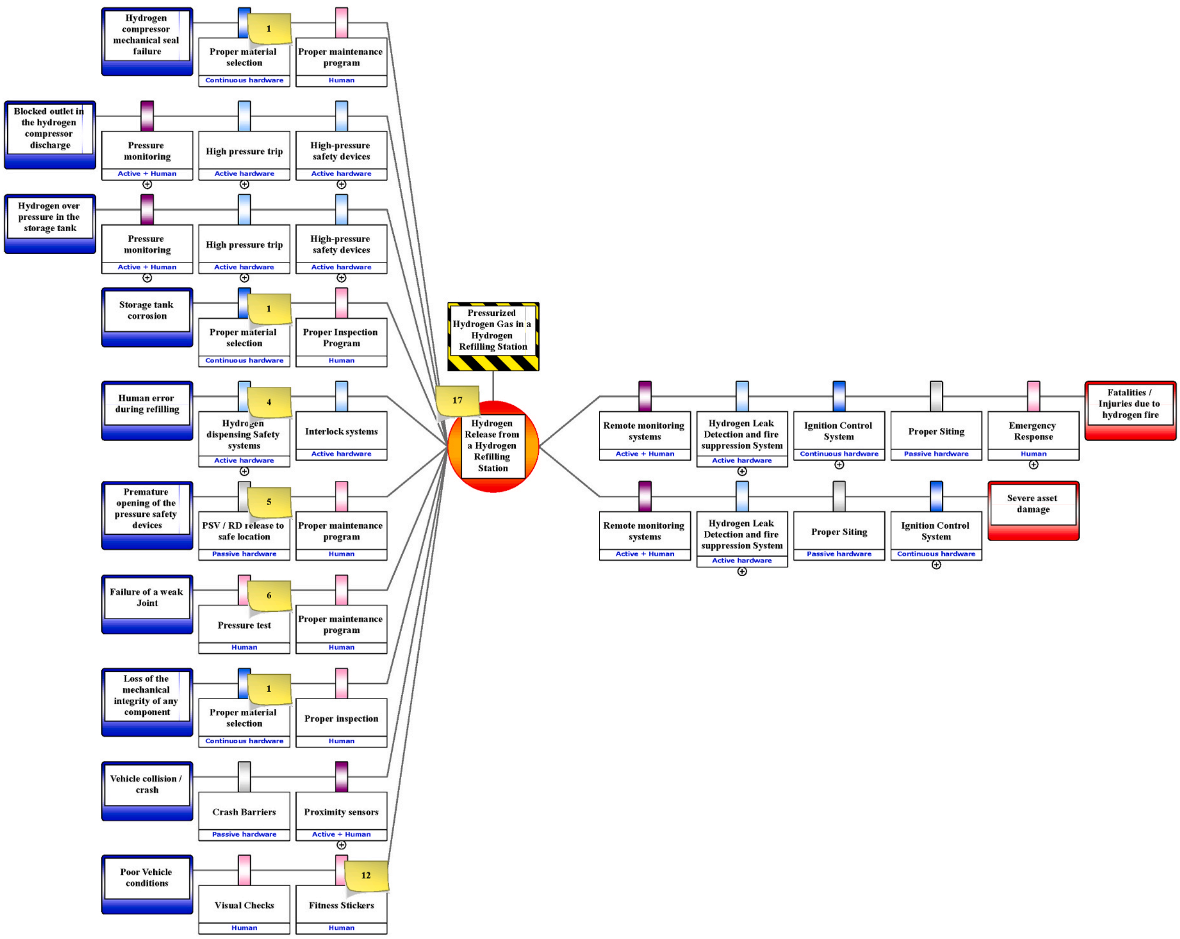

Fig. 4. HRS bowtie diagram.

Figs. 6 and 7 display the barrier analysis for the hydrogen Fuel Cell Vehicle:

Table 8 comprise all activities that were recommended in the Hydrogen Vehicle Bowtie Barrier Analysis.

3.3. Parking/repair garages

In light of the absence of regulatory guidelines that address the crucial criteria for enclosed structures designed for parking or repairing hydrogen vehicles, especially those with limited or inadequate ventilation that may lead to the accumulation of accidental hydrogen releases and subsequent adverse outcomes, there has been a request to evaluate the associated risks. Additionally, there is a need to provide recommendations for the effective mitigation of potential hazards in enclosed parking and repair garages designated for hydrogen-powered vehicles.

3.3.1. Preliminary hazard identification using SWIFT

During the SWIFT workshop, four significant concerns were raised for discussion.

These concerns included:

- The ventilation;
- The design;
- Maintenance of the safety systems;
- The accidental releases;

For each of these concerns, the underlying reasons behind the issues were explored and potential consequences that might arise if these concerns were not adequately addressed were also examined. Finally, recommendations were proposed with the aim of mitigating the associated risks.

Table 9 is the private/repair garage SWIFT Worksheet:

3.3.2. Bowtie barrier analysis

Figs. 8 and 9 display the barrier analysis for the hydrogen Fuel Cell Vehicle:

4. Discussion

In this study, the SWIFT methodology is initially employed to screen all hazardous scenarios that could lead to Loss of Primary Containment (LOPC), fire, and explosions. SWIFT serves as a systematic hazard identification method to capture a wide range of potential risks across the case studies.

Following this preliminary hazard identification, the bowtie analysis is used to visualize these scenarios and provide an in-depth examination of the associated barriers. Specifically, if SWIFT identified recommendations to prevent or mitigate a particular hazardous scenario, bowtie diagrams were employed to analyse those recommendations in greater depth. The bowtie method helps identify potential degradations in the barriers and suggests additional measures to ensure the effectiveness of the safeguards.

The combination and interaction of SWIFT and bowtie ensure a comprehensive approach to risk management. Without a rigorous hazard identification method like SWIFT, some key hazards may have been overlooked during bowtie development. Conversely, relying solely on SWIFT might not fully account for the potential degradation of safeguards, which could reduce their effectiveness over time. Thus,

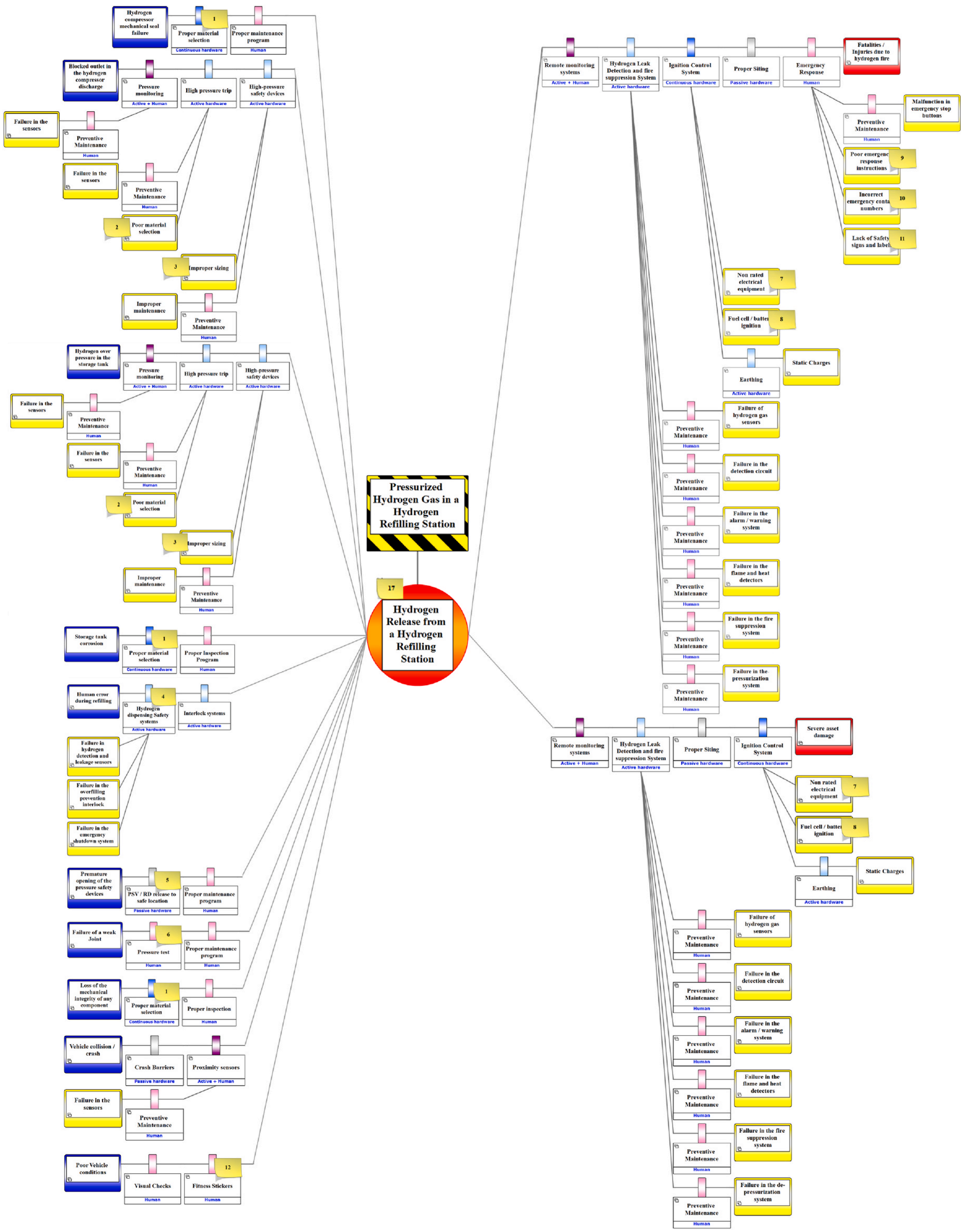

Fig. 5. HRS bowtie diagram with degradation factors and degradation controls.

integrating both techniques allows for a more robust risk reduction strategy by identifying hazards early and ensuring that the proposed safeguards are thoroughly evaluated and reinforced.

Using SWIFT and bowtie barrier analysis for the three cases (HRS, Hydrogen vehicle, and parking/repair garages) has revealed a set of recommendations that require focus and consideration during the following project stages and during execution.

The raised recommendations can be categorized into two main categories:

- **Actions** to minimize the risk;
- **Activities** to assure the sustainability of the safety reduction measures along the lifetime of the project (from the production of vehicles to the demolition).

In the following section, each action and activity raised from the utilized risk assessment studies will be analysed in more details and linked with the supporting reference from industry best practices or previous research paper where exist.

Table 5
Bowtie barrier analysis list of actions.

Code	Name	Description	Action party
1	Applicable codes and standards	Assure that the equipment is designed as per the last updated globally recognized (code/ standard).	Engineering
2	SIS Devices	Assure that the required integrity of the identified safety instrumented devices are properly addressed through SIL assessment study and the purchased devices as compatible with the study results through SIL verification study.	Engineering
3	Proper Sizing	Assure the proper sizing of the relief devices as per the globally recognized standards such as API 520, 526, 527, and 521	Engineering
4	Safe Joints/ Couplings	Assure the presence of quick breakaway joints and dry disconnect couplings in case of accidental movement of the vehicle during the filling process.	Engineering
5	Relief Location	Assure that all relief discharge is directed to safe location and to the top for safe dispersion (No shelters or any kind of obstructions should exist in front of the relief discharge direction).	Engineering
6	Helium Leak Test	Assure that the whole system is tested against potential leaks using helium before pressurizing the system with hydrogen.	Operations
7	ATEX Equipment	Assure that the hazardous area classification study is conducted and all existing electrical equipment are compliant with the hazardous area classification.	Engineering
8	ATEX Enclosure	Assure that the vehicle electrical components are enclosed by explosion proof enclosure.	Engineering
9	ERP	Assure that the emergency response plan is properly developed, reviewed and approved by the legal authorities and staff have received practical training on its usage.	HSE Department
10	ERP Update	Assure the ERP is periodically checked and updated if required.	HSE Department
11	Warning Signs	Assure the presence of the warning signs in each equipment in the station and in locations visible to the general public. The warning signs should present the type of hazard and the required action in case of emergency situations.	HSE Department
12	Fitness Stickers	Assure that the vehicle holds a valid fitness sticker that confirms the vehicle last regulatory inspection and valid license for use. The fitness sticker should be renewed annually.	
13	Human Factors	Assure that the vehicle design considers the human factors and provides engineering solutions to minimize human errors.	Engineering
14	Competence Assurance	Assure that maintenance technicians are properly trained and qualified to conduct the required maintenance activities safely and effectively	Maintenance
15	Ventilation Design	Assure that enclosed places where hydrogen vehicle are either parked or maintained are properly ventilated to minimize any hydrogen accumulation.	Engineering
16	Approval License	Parking and repair garages shall obtain an acceptance license from legal authorities. The license should be renewed periodically after periodic audits to assure the compliance with the legal requirements.	Third Party
17	Fitness for operation license	Hydrogen refuelling stations shall obtain an acceptance from legal authorities. The license should be renewed periodically after periodic audits to assure the compliance with the legal requirements.	Third Party

4.1. Recommended actions

The SWIFT and Bowtie analyses have identified a set of recommendations which are organized, here, in three categories of recommended actions, each targeting different aspects of risk reduction as outlined below:

- Actions to add/enhance hardware safety barriers;

These actions focus on the physical measures that need to be implemented or improved to minimize risks. They include adding or upgrading safety features on equipment, systems, or installations (e.g., safety valves, fire suppression systems, or containment barriers). The rationale behind this is the fact that hardware safety barriers are critical as the first line of defence in controlling hydrogen-related risks.

- Actions to promote human performance;

Actions in this category are aimed at improving the performance, skills, and behaviour of personnel involved in the operation and maintenance of hydrogen systems. The rationale of promoting these actions is the fact that effective human performance is essential to ensure that safety measures are properly executed and maintained throughout the project lifecycle.

- Actions to enhance the management system.

These actions seek to enhance the overall safety management system. This includes better risk communication, clearer roles and responsibilities, regular safety tests, and integrating lessons learned into continuous improvement processes. A well-structured safety management system ensures that both hardware and human performance measures are consistently applied and maintained.

Each action is analysed in detail with its origin clearly identified from the SWIFT or Bowtie analysis, referencing specific sections or tables with a detailed description of the action. The rationale for its implementation is discussed in notes, linking it to the overall risk mitigation strategy, and validated by referencing industry best practices or previous research.

4.1.1. Actions to add/enhance hardware safety barriers

Action 1: Secure the required spare parts.

✓ Type: Hardware; Source: SWIFT 1.6.1.1.2 & 2.3.1.1.2
- *Action's description*: See Tables 4&7
- *Notes*: Having spare parts readily available and performing regular component replacements helps prevent equipment failure and ensures uninterrupted operations.
- *Supporting References*: [50].

Action 2: Emergency Shutdown Switches.

Table 6
HRS bowtie barrier analysis list of activities.

Code	Details	Category	Frequency	Responsible	Barriers
1	Preventive/Predictive Maintenance Conduct the required preventive and predictive maintenance activities as per the vendor requirements.	Maintenance	As required	Maintenance	Proper maintenance program Preventive Maintenance Proximity sensors
2	Inspection Conduct the required inspections as per the vendor requirements	Inspection	As required	Maintenance	Proper inspection Hydrogen dispensing Safety systems Remote monitoring systems Hydrogen Leak Detection and fire suppression System Proper Inspection Program
3	Periodical ERP Mock Drills Apply mock drills periodically to enhance Emergency Response Readiness		3 Monthly	HSE Department	Emergency Response
4	Earthing and grounding checks Conduct periodic Earthing and grounding checks on the existing equipment		3 Monthly		Earthing
5	Visual Checks Assure that there is no obvious damage/defect in the vehicle that could pose safety issue.	Inspection	Continuous		Visual Checks

Table 7
Hydrogen vehicle SWIFT worksheet.

What if?	Reason of Concern	Potential Consequences	Recommendations
2.1 Inadequate design	2.1.1 Lack of previous knowledge	2.1.1.1 Inadequate design could lead to accidental release of hydrogen and fire.	2.1.1.1.1 Vehicle prototype should be reviewed and approved, and then pilot examinations with all recognized tests should be conducted.
	2.2.2 New design		2.1.1.1.2 Accreditation from certified organizations should be obtained before introduction of the new model to the general public.
2.2 Poor driver behavior	2.2.1 Lack of risk perception	2.2.1.1 Poor behaviour of individuals could lead to accidental release of hydrogen and fire	2.2.1.1.1 Drivers with bad record of driving violations should not be permitted to use hydrogen vehicles during the initial stages of the project. 2.2.1.1.2 Assure the presence of warning signs and alarms, and CCTV system. 2.2.1.1.3 Assure the design of the vehicle is inherently safe and considers human failure. 2.2.1.1.4 Assure the presence and effectiveness of the fire and gas detection, fire-fighting equipment.
2.3 Poor maintenance	2.3.1 Inadequate maintenance program 2.3.2 Lack of maintenance tools or spare parts.	2.3.1.1 Poor maintenance could lead to failure in critical components. This could result in hydrogen release and fire with potential for fatalities and asset damage.	2.3.1.1.1 Assure the adequacy of the maintenance and inspection programs 2.3.1.1.2 Secure the required maintenance tools and spare parts for safety critical equipment and replace them before the end of their end of life or in case of discovering unacceptable damage.
	2.3.3 Lack of competencies		2.3.1.1.3 Comprehensive training and competence assessment programs are required for personnel maintaining hydrogen vehicles.
2.4 Aging of the vehicle and its components	2.4.1 Material Deterioration due to wear/tear and other damage mechanisms	2.4.1.1 Sudden and repeated failure in critical components could occur. This could result in hydrogen release and fire with potential for fatalities and asset damage.	2.4.1.1.1 Assure that vehicle license will not be issued in case of non-compliance with the maintenance programs (license to be renewed on annual basis). 2.4.1.1.2 Refer to 2.3.1.1.1 2.4.1.1.3 Refer to 2.3.1.1.2
2.5 Accidental releases and/or fire	2.5.1 Refer to 1.7.1		
2.6 Crash/Collision	2.6.1 Loss of the control system	2.6.1.1 Potential for hydrogen release and fire with potential for fatalities and asset damage.	2.6.1.1.1 Assure that the hydrogen inventory is protected with double containment barriers and in case of catastrophic vehicle crash, releases are diverted upward to minimize surroundings damage.
	2.6.2 Loss of driver focus 2.6.3 Bad road conditions 2.6.4 Error for other drivers		2.6.1.1.2 Refer to 2.1.1.1.1, 2.1.1.1.2 and 2.2.1.1.1
2.7 Deliberate damage	2.7.1 Lack of security	2.7.1.1 Potential for hydrogen release and fire with potential for fatalities and asset damage.	2.7.1.1.1 Promote the security infrastructure through the installation of surveillance CCTV systems and security patrolling, if required. 2.7.1.1.2 Refer to 2.1.1.1.1, 2.1.1.1.2, 2.2.1.1.1, and 2.6.1.1.1

✓ Type: Hardware; Source: SWIFT 1.7.1.1.1

- *Action's description*: See Table 4
- *Notes*: Readily available emergency shutdown switches are crucial for promptly addressing safety concerns and minimizing risks.
- *Supporting References*: [51–53].

4.1.2. Action 3: fire and gas detection equipment

✓ Type: Hardware; Source: SWIFT 1.7.1.1.2 & 2.2.1.1.4

- Action's description: See Tables 4&7

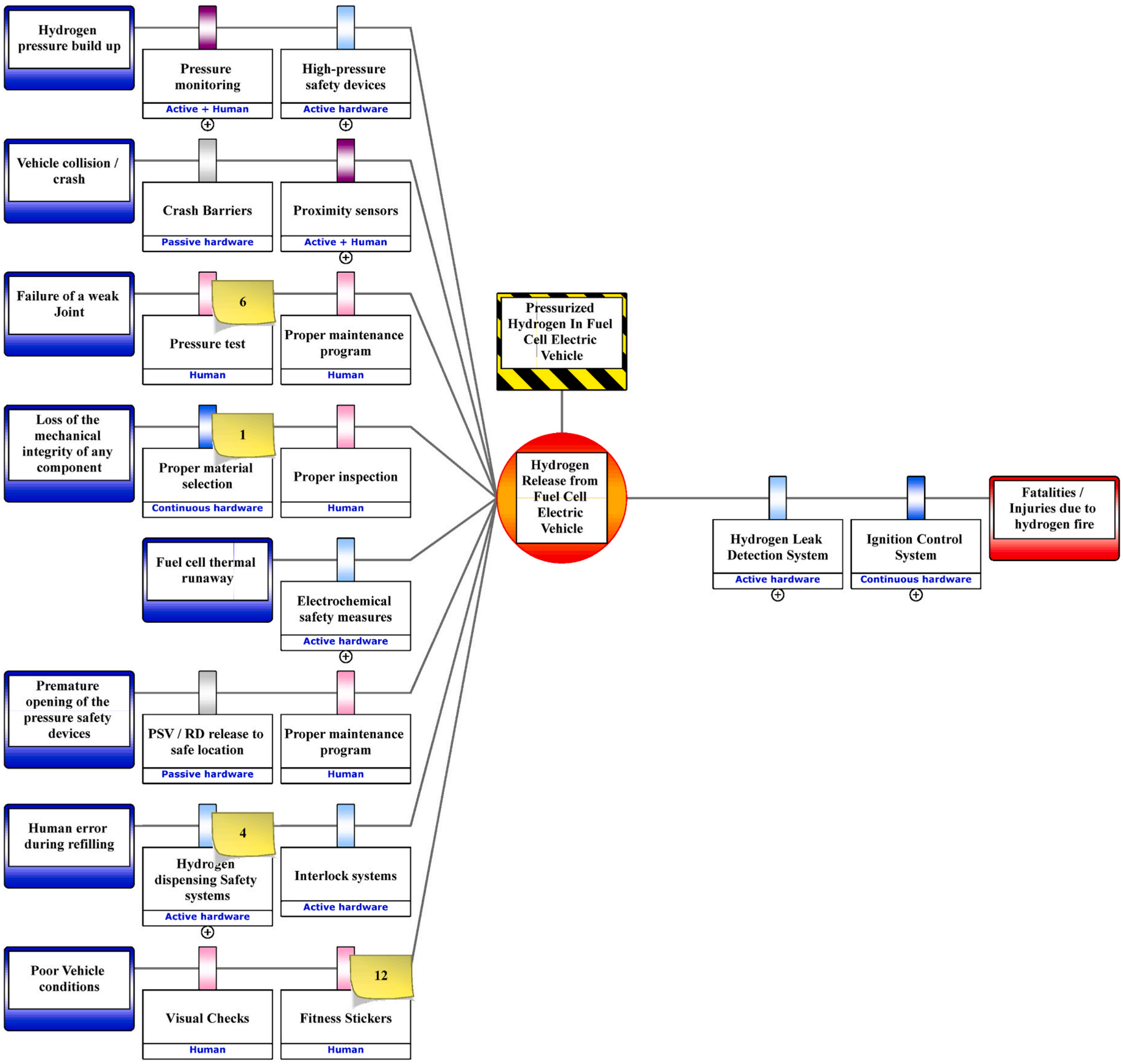

Fig. 6. Hydrogen fuel cell vehicle bowtie diagram.

- *Notes*: Fire and gas detection systems, along with proper fire-fighting equipment, are essential for preventing and responding to fires at the station.
- *Supporting References*: [54–57].

Action 4: Minimize Ignition Sources.

✓ Type: Hardware; Source: SWIFT 1.7.1.1.3
- Action's description: See Table 4
- *Notes*: Removing potential ignition sources like electrical equipment, heat, and smoking helps prevent fires and explosions, ensuring the safety of the station and its surroundings.
- *Supporting References*: [58].

Action 5: Warning Signs and CCTV.

✓ Type: Hardware; Source: SWIFT 1.8.1.1.1 & 2.2.1.1.2
- Action's description: See Tables 4&7
- *Notes*: Warning signs, alarms, and CCTV surveillance work together to improve safety by alerting people to hazards and allowing for rapid responses.
- *Supporting References*: [59,60].

Action 6: Safe Dispensing System Design.

✓ Type: Hardware; Source: SWIFT 1.8.1.1.2
- Action's description: See Table 4
- *Notes*: A safe dispensing system prevents human error and protects people by maintaining control even when mistakes happen.
- *Supporting References*: [52,61]

Action 7: Safe Vehicle Design.

✓ Type: Hardware; Source: SWIFT 2.2.1.1.3
- *Action's description*: See Table 7
- *Notes*: Inherently safe design proactively prevents human error by building in safeguards. This approach creates a robust system less likely to experience accidents or malfunctions due to human errors.
- Supporting *References*: [62,63].

Action 8: Hydrogen Inventory Protection Using Double Containment Barriers.

✓ Type: Hardware; Source: SWIFT 2.6.1.1.1
- Action's description: See Table 7

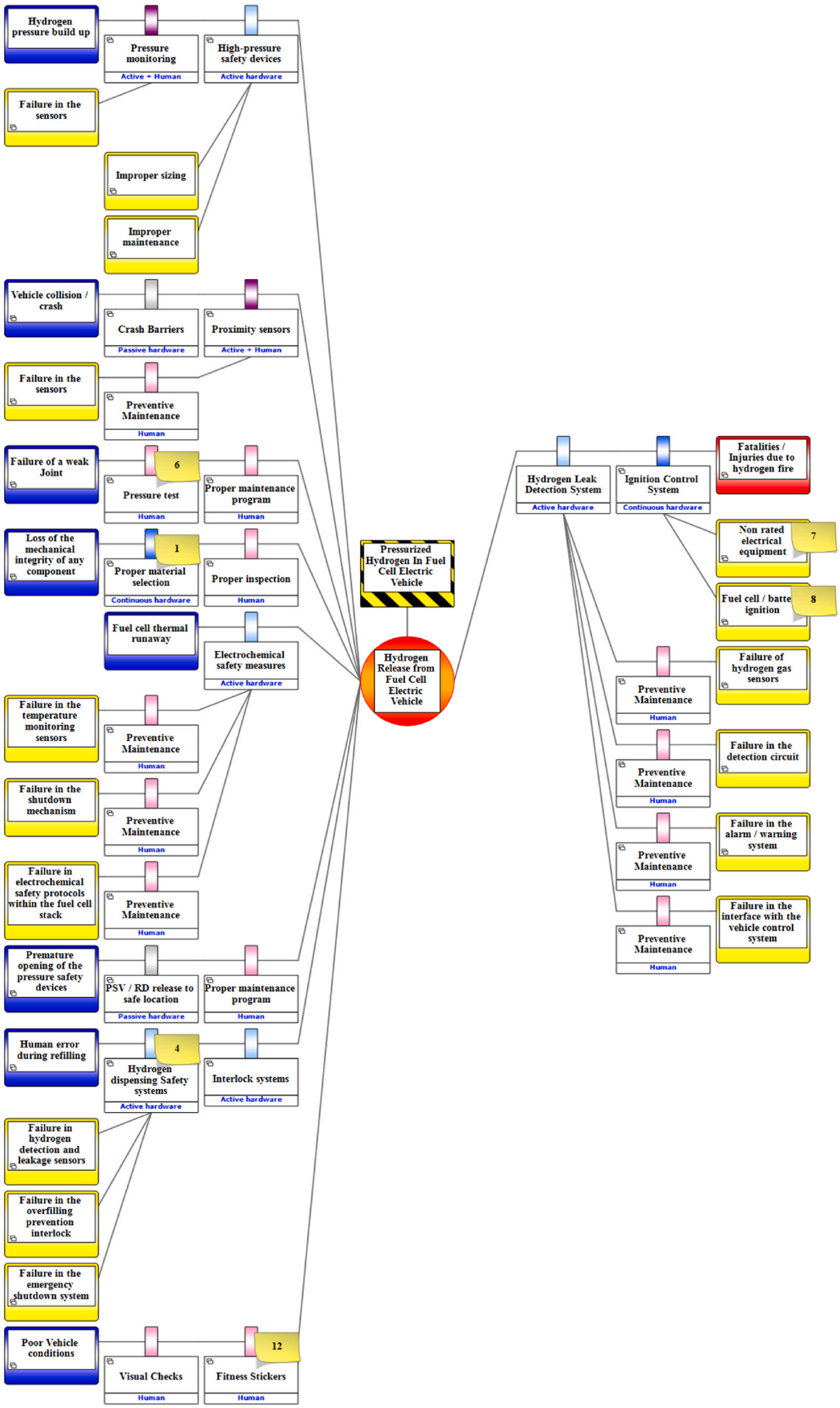

Fig. 7. Hydrogen fuel cell vehicle bowtie diagram with degradation factors and degradation controls.

Table 8
Hydrogen vehicle bowtie barrier analysis list of activities.

Code	Details	Category	Frequency	Responsible	Barriers
1	**Preventive/Predictive Maintenance** Conduct the required preventive and predictive maintenance activities as per the vendor requirements.	Maintenance	As required	Maintenance	Proper maintenance program Preventive Maintenance Proximity sensors
2	**Inspection** Conduct the required inspections as per the vendor requirements	Inspection	As required	Maintenance	Proper inspection Hydrogen dispensing Safety systems
5	**Visual Checks** Assure that there is no obvious damage/defect in the vehicle that could pose safety issue.	Inspection	Continuous		Visual Checks

Table 9
Hydrogen Enclosed private/Repair SWIFT Worksheet.

What if?	Reason of Concern	Potential Consequences	Recommendations
3.1 Inadequate ventilation	3.1.1 Parking or repairing vehicles garages are in residential buildings or in congested area	3.1.1.1 Potential for accumulation of accidental hydrogen releases that could lead to confined vapor cloud explosion	3.1.1.1.1 Assure that the FCEV parking and repair garages are properly ventilated. 3.1.1.1.2 Assure that the existing lighting and electrical devices in the upper level of repair garages are ATEX certified to minimize the presence of ignition probability.
3.2 Inadequate design or construction	3.2.1 Lack of guidance to design FCEV repair garages	3.2.1.1 Potential of under-design of the required safety measures that could lead to hydrogen accumulations with potential for fire/explosion	3.2.1.1.1 Develop clear and comprehensive instructions for the design, installation, operation, and maintenance that must be strictly followed to obtain the operating license for FCEV repair garages. 3.2.1.1.2 During the design phase, well before construction, develop, review, and gain approval for the adequacy and sufficiency of the safety measures from the authorized parties and legal authorities.
3.3 Poor maintenance program for the safety measures (ventilation, detectors, and fire protection)	3.3.1 Usage of improper tools 3.3.2 Lack of competency	3.3.1.1 Degradation/deactivation of the hydrogen detection and protection systems that could lead to the inability either to prevent, detect or protect against hydrogen accumulation and fire/explosion	3.3.1.1.1 Ensure only approved tools are used for working on high-pressure hydrogen components. 3.3.1.1.2 Ensure proper training for technicians to handle hydrogen detection and protection systems safely.
3.4 Accidental releases and/or fire	3.4.1 Refer to 1.7.1		

- *Notes*: Double containment barriers provide a robust defence against accidental hydrogen release. Designed to handle worst-case scenarios, the system directs potential releases upwards, minimizing environmental impact.
- *Supporting References*: [52,60].

Action 9: Security Infrastructure.

✓ Type: Hardware; Source: SWIFT 2.7.1.1.1
- Action's description: See Table 7
- *Notes*: CCTV surveillance and security patrols work together to prevent incidents and maintain a safe environment.

Action 10: Ventilation in Garages.

✓ Type: Hardware; Source: SWIFT 3.1.1.1.1
✓ SWIFT Finding: Inadequate ventilation
- *Action's description*: See Table 9
- *Notes*: Ventilation systems are crucial for removing harmful gases, protecting people and vehicles, and preventing fires.
- *Supporting References*: [52,64].

Action 11: ATEX Certified Lighting and Electrical Devices.

✓ Type: Hardware; Source: SWIFT 3.1.1.1.2
- Action's description: See Table 9
- *Notes*: ATEX-certified lighting and electrical equipment is specifically designed for safe operation in environments with flammable gases like hydrogen. By using this certified equipment, the garage significantly reduces the risk of ignition and accidents.
- Supporting References: [58]

Action 12: Approved Tools for High-Pressure Hydrogen.

✓ Type: Hardware; Source: SWIFT 3.3.1.1.1
- Action's description: See Table 9
- *Notes*: This approach minimizes the risk of errors, leaks, or damages that could arise from using incorrect tools.

Action 13: Equipment Design Standards.

✓ Type: Hardware; Source: Bowtie
✓ Bowtie Finding: Threat: HRS or hydrogen vehicle components failure/Loss of the mechanical integrity of any component.
- *Action's description*: See Table 5 (code 1)
- *Notes*: Adhering to the latest codes and standards is essential for equipment design. This ensures safety, efficiency, and compliance while demonstrating a commitment to industry best practices.
- Supporting References: [52, 60]

Action 14: Safety Instrumented Devices Integrity.

✓ Type: Hardware; Source: Bowtie
✓ Bowtie Finding: Threat: Blocked outlet in the hydrogen compressor discharge

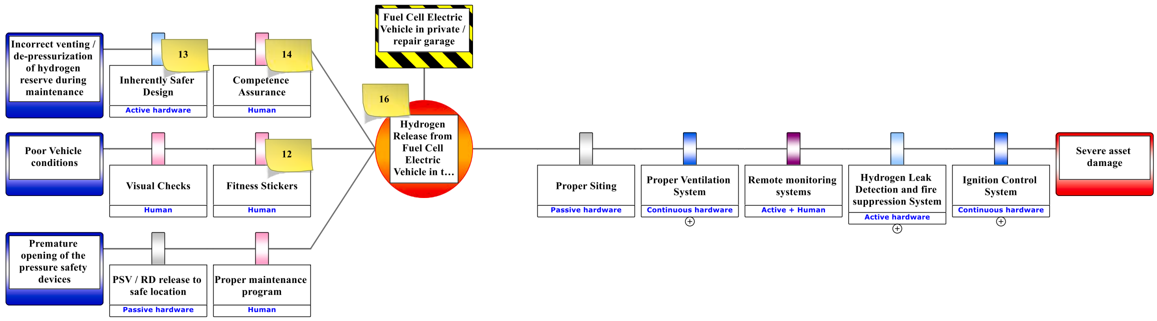

Fig. 8. Hydrogen vehicle private/repair garage bowtie diagram.

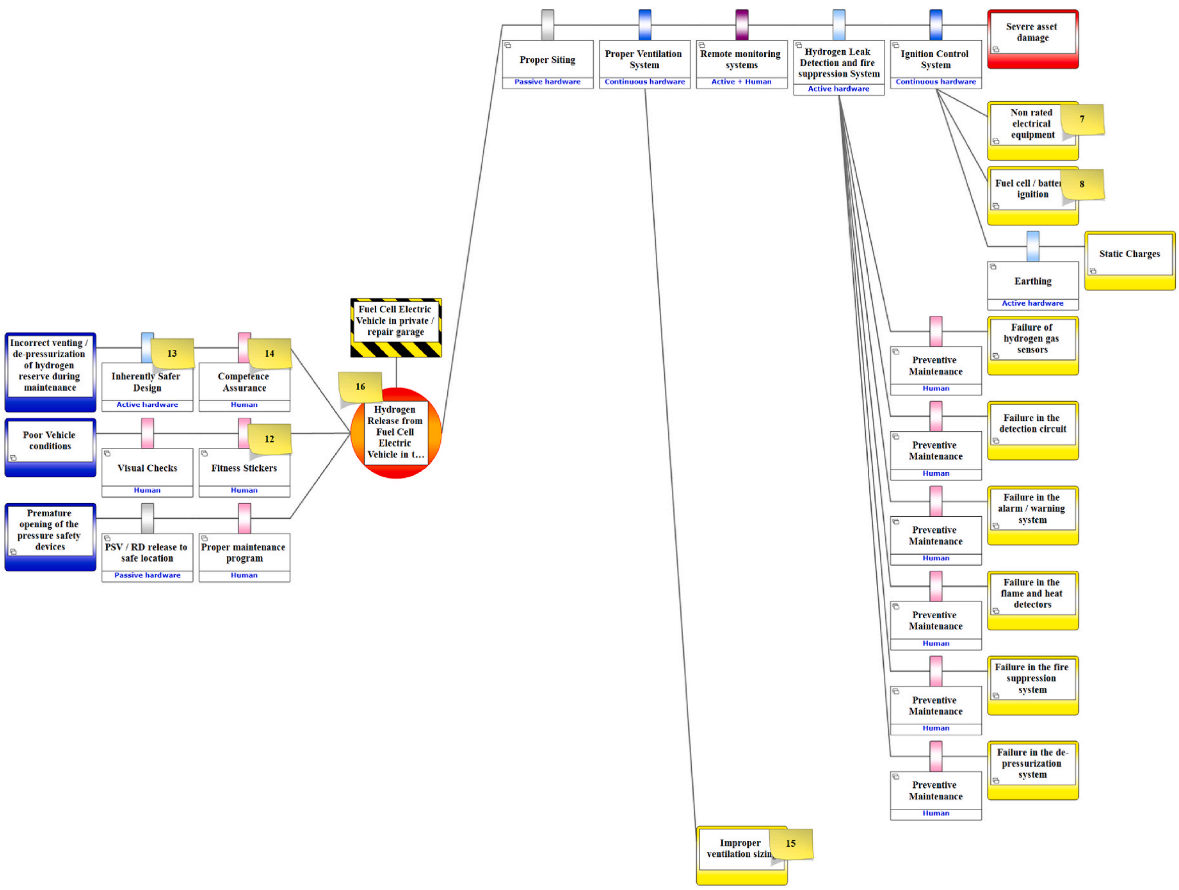

Fig. 9. Hydrogen fuel cell vehicle private/repair garage bowtie diagram with degradation factors and degradation controls.

- *Action's description*: See Table 5 (code 2)
- *Notes*: By assessing the reliability of safety devices through SIL evaluation and verifying their compatibility, the station ensures that safety measures are both planned and effectively implemented. This approach reduces risks and improves overall safety.
- *Supporting References*: [65].

Action 15: Proper Sizing of Safety Devices.

✓ Type: Hardware; Source: Bowtie
✓ Bowtie Finding: Threat: Blocked outlet in the hydrogen compressor discharge

- *Action's description*: See Table 5 (code 3)
- *Notes*: This requirement ensures that pressure-related risks are effectively mitigated, safeguarding equipment and personnel.
- *Supporting References*: [66,67].

Action 16: Quick Breakaway Joints and Dry Disconnect Couplings.

✓ Type: Hardware; Source: Bowtie
✓ Bowtie Finding: Threat: Human error during refuelling

- *Action's description*: See Table 5 (code 4)
- *Notes*: Quick breakaway joints and dry disconnect couplings serve as safety features during vehicle refuelling. These mechanisms automatically disconnect in case of accidental movement, protecting station equipment and preventing hydrogen release. This approach prioritizes safety by minimizing risks to personnel and the station.
- *Supporting References*: [68,69].

Action 17: Safe Relief Discharge.

✓ Type: Hardware; Source: Bowtie

✓ Bowtie Finding: Threat: Premature opening of the pressure safety devices
- *Action's description*: See Table 5 (code 5)
- *Notes***:** Directing gas discharge upwards to a safe location minimizes hazards and ensures controlled dispersion. Preventing obstructions in the discharge path avoids hydrogen accumulation and the risk of explosion.
- Supporting *References*: [62,66]

Action 18: Hazardous Area Classification Compliance.

✓ Type: Hardware; Source**:** Bowtie
✓ Bowtie Finding: Degradation Factor: Presence of Non-rated electrical equipment
- *Action's description*: See Table 5 (code 7)
- *Notes***:** A hazardous area classification study identifies potential explosion risks and ensures that electrical equipment is suitable for the environment. This safeguards against ignition sources, preventing accidents and promoting safety.
- Supporting References: [58]

Action 19: Explosion-Proof Vehicle Electrical Components.

✓ Type: Hardware; Source**:** Bowtie
✓ Bowtie Finding: Degradation factor: Fuel cell/battery ignition
- *Action's description*: See Table 5 (code 8)
- *Notes***:** Enclosing vehicle electrical components in explosion-proof enclosures prevents sparks and electrical malfunctions from igniting flammable gases like hydrogen.

Action 20: Warning Signs.

✓ Type: Hardware; Source**:** Bowtie
✓ Bowtie Finding: Degradation Factor: Lack of Safety signs and labels
- *Action's description*: See Table 5 (code 11)
- *Notes***:** Warning signs promote safety by informing people about hazards and emergency procedures.

Action 21: Human Factors in Vehicle Design.

✓ Type: Hardware; Source**:** Bowtie
✓ Bowtie Finding: Threat: Incorrect venting/de-pressurization of hydrogen reserve during maintenance.
- *Action's description*: See Table 5 (code 13)
- *Notes***:** By addressing human factors and integrating solutions to minimize errors, the vehicle design prioritizes safety.
- *Supporting References*: [70].

4.1.3. *Actions to promote human performance*

Action 22: Operator Experience and Training.

✓ Type: Human; Source**:** SWIFT 1.3.1.1.1 & 1.5.1.1.1
- Action's description: See Table 4
- *Notes***:** Hiring experienced personnel is preferred for HRS operation, but comprehensive training is essential for those without experience.
- *Supporting References*: [60].

Action 23: Training for Vehicle Maintenance Personnel.

✓ Type: Human; Source**:** SWIFT 2.3.1.1.3
- Action's description: See Table 7
- *Notes***:** Inadequate maintenance of critical components can lead to hydrogen leaks, fires, and fatalities. Comprehensive training and competency assessment for maintenance personnel ensure proper care of complex hydrogen vehicle systems. This approach safeguards against accidents, extends vehicle lifespan, and fosters public trust in hydrogen technology.
- *Supporting References*: [52,71].

Action 24: Technician Training for Detection Systems.

✓ Type: Human; Source**:** SWIFT 3.3.1.1.2
- Action's description: See Table 9
- *Notes***:** This requirement ensures that technicians possess the skills and knowledge required to handle hydrogen detection and protection systems. This approach guarantees that these systems remain in optimal working condition that will foster a secure environment.
- *Supporting References*: [52].

Action 25: Ventilation in Enclosed Areas.

✓ Type: Human; Source**:** Bowtie
✓ Bowtie Finding: Degradation factor: Improper ventilation sizing.
- *Action's description*: See Table 5 (code 15)
- *Notes***:** Proper ventilation in enclosed spaces prevents hydrogen accumulation, reducing the risk of fire and explosion.
- Supporting References: [52,64,72].

4.1.4. *Actions to enhance management systems*

Action 26: Clear Instructions for Operations.

✓ Type: System; Source**:** SWIFT 1.1.1.1.1; 1.4.1.1.1; 3.2.1.1.1
- *Action's description*: See Tables 4&9
- *Notes***:** The new installation of hydrogen refuelling stations in many countries faces challenges due to a lack of knowledge and guidance. This can lead to unsafe locations in congested areas and inadequate safety measures or maintenance, increasing the risk of fires or explosions. To mitigate these risks, it is crucial to provide clear guidance for hydrogen vehicle manufacturers, refuelling station operators, and service garages.
- *Supporting References*: [73,74].

Action 27: Safety Demonstration by Operators.

✓ Type: System; Source**:** SWIFT 1.1.1.1.2
- Action's description: See Table 4
- *Notes***:** Before constructing a hydrogen refuelling station, it is essential to obtain prior authorization for the chosen site. The operator must demonstrate their ability to safely manage the station by producing a comprehensive safety report. This report should detail the site, station layout, equipment design, operational procedures, staff qualifications, and a thorough risk assessment. A robust risk mitigation strategy is required to reduce risks to an acceptable level (ALARP).
- *Supporting References*: [73,75].

Action 28: Emergency Response Plan (ERP).

✓ Type: System; Source**:** SWIFT 1.1.1.1.3, 1.7.1.1.4, Bowtie
✓ SWIFT/Bowtie Finding: Potential difficulties in emergency response/ Poor Emergency Response Plan.
- *Action's description*: See Tables 4 and 5 (Code 9)
- *Notes***:** Effective emergency preparedness is crucial for hydrogen refuelling stations. Engaging with emergency management authorities like civil defence and fire departments early in the project is essential. Sharing the ERP with them allows for valuable input, ensuring the plan aligns with local emergency protocols and resources. This collaborative approach significantly reduces risks during operations.
- *Supporting References*: [69,73,75]

Action 29: Secure Access for Emergency Response.

✓ Type: System; Source: SWIFT 1.1.1.1.4
- Action's description: See Table 4
- *Notes*: Clear access routes for emergency responders are essential for effective incident management.

Action 30: Site Selection.

✓ Type: System; Source: SWIFT 1.1.1.1.5
- Action's description: See Table 4
- *Notes*: The location of a hydrogen refuelling station should consider traffic and population density to facilitate emergency response.

Action 31: Training for Refuelling Station Personnel.

✓ Type: System; Source: SWIFT 1.3.1.1.2
- Action's description: See Table 4
- *Notes*: Thorough training and competency evaluation are essential for station personnel. This ensures safe and efficient operations, enabling effective handling of potential challenges.
- Supporting References: [60]

Action 32: Maintenance and Inspection Programs.

✓ Type: System; Source: SWIFT 1.6.1.1.1 & 2.3.1.1.1
- Action's description: See Tables 4&7
- *Notes*: Effective maintenance and inspection programs are essential for ensuring equipment reliability and safety. These programs must be comprehensive, consistently implemented, and regularly evaluated to prevent equipment failures, minimize downtime, and maintain operational excellence.
- *Supporting References*: [50,52]

Action 33: Vehicle Prototype Review and Testing.

✓ Type: System; Source: SWIFT 2.1.1.1.1
- *Action's description*: See Table 7
- *Notes*: Thorough review, approval, and pilot testing are essential before mass production of hydrogen vehicles. These processes ensure the prototype meets safety, performance, and efficiency standards, preparing the vehicle for widespread adoption.

Action 34: Accreditation for New Vehicle Models.

✓ Type: System; Source: SWIFT 2.1.1.1.2
- Action's description: See Table 7
- *Notes*: Third-party verification instils consumer confidence by confirming adherence to industry standards. This strengthens market acceptance and reinforces the manufacturer's commitment to delivering reliable and trustworthy vehicles.

Action 35: Driving Record Restrictions.

✓ Type: System; Source: SWIFT 2.2.1.1.1
- Action's description: See Table 7
- *Notes*: By carefully selecting drivers with clean driving records, the project mitigates the risk of accidents and protects its reputation during the initial stages. This proactive approach prioritizes safety, fosters a responsible driving culture, and establishes a positive foundation for future success.

Action 36: Compliance for Vehicle Licensing.

✓ Type: System; Source: SWIFT 2.4.1.1.1
- Action's description: See Table 7
- *Notes*: Mandating maintenance program adherence for vehicle licensing ensures that hydrogen vehicles meet safety and performance standards. This promotes regular maintenance, minimizes malfunctions, and contributes to a safer hydrogen transportation ecosystem.

Action 37: Safety Measure Approval.

✓ Type: System; Source: SWIFT 3.2.1.1.2
- Action's description: See Table 9
- *Notes*: By conducting a thorough evaluation of safety protocols and obtaining approvals from relevant authorities and regulatory bodies, the garage demonstrates a proactive commitment to compliance.

Action 38: Leak Testing.

✓ Type: System; Source: Bowtie
✓ Bowtie Finding: Threat: Failure of a weak Joint
- *Action's description*: See Table 5 (Code 6)
- *Notes*: Pre-filling the system with helium to detect and repair leaks before introducing hydrogen is a critical safety measure. This proactive approach minimizes the risk of accidents by ensuring system integrity.

Action 39: Licensing for Garages.

✓ Type: System; Source: Bowtie
✓ Bowtie Finding: The top event: Hydrogen Release from Fuel Cell Electric Vehicle in the enclosed parking/repair garage
- *Action's description*: See Table 5 (Code 16)
- *Notes*: Regular audits and license renewals guarantee ongoing compliance with legal and safety standards. This proactive approach demonstrates the garage's commitment to responsible hydrogen management.

Action 40: Regular ERP Updates.

✓ Type: System; Source: Bowtie
✓ Bowtie Finding: Degradation Factor: Incorrect emergency contact numbers.
- *Action's description*: See Table 5 (Code 10)
- *Notes*: Regularly reviewing and updating the Emergency Response Plan (ERP) ensures its effectiveness in handling emergencies. This commitment to safety guarantees that station personnel are well-prepared to respond to unforeseen incidents swiftly and efficiently.

Action 41: Vehicle Fitness Sticker.

✓ Type: System; Source: Bowtie
✓ Bowtie Finding: Threat: Poor Vehicle conditions
- *Action's description*: See Table 5 (Code 12)
- *Notes*: A valid and visible fitness sticker and license demonstrate compliance with roadworthiness regulations. Regular vehicle inspections ensure safety and functionality, reducing the risk of operating unsafe vehicles on public roads.

4.2. Recommended activities

Required activities that aim to assure the sustainable functionality and dependency of the new systems were identified during the bowtie barrier analysis.

These activities can be categorized into two categories:

1 Activities to assure sustainable and dependable human performance.

2 Activities to assure sustainable and dependable equipment performance.

The rationale behind each identified activity is described in this section:

Activity 1: Preventive and Predictive Maintenance.

✓ Type: Preventive/Predictive Maintenance; Frequency: As determined
 • *Activity's description*: Conduct the required preventive and predictive maintenance activities as per the vendor requirements (See Tables 6 and 8).

Activity 2: Inspections.

✓ Type: Inspection; Frequency: As determined
 • *Activity's description*: Conduct the required inspections as per the vendor requirements (See Tables 6 and 8).

Activity 3: Emergency Response Mock Drills.

✓ Type: Periodical ERP Mock Drills; Frequency: 3 months
 • *Activity's description*: Apply mock drills periodically to enhance Emergency Response Readiness (See Table 6).

Activity 4: Earthing and Grounding Checks.

✓ Type: Earthing and grounding checks; Frequency: 3 months
 • *Activity's description*: Conduct periodic earthing and grounding checks on the existing equipment (See Table 6).

Activity 5: Vehicle Safety Check Before Refuelling.

✓ Type: Visual Checks; Frequency: Continuous
✓ *Activity's description*: Assure that there is any obvious damage/defect in the vehicle that could pose safety issue before start hydrogen refuelling (See Tables 6 and 8).

5. Conclusion

This paper focused on mitigating risks in end-user hydrogen applications within the transportation sector, examining a hypothetical pilot initiative to introduce hydrogen infrastructure in a country's transportation system. The initiative began with the development of hydrogen refuelling stations, vehicles, and maintenance facilities. During the conceptual design phase, we employed informative risk assessment techniques, specifically SWIFT and Bowtie analysis, to identify and screen significant concerns related to the construction, operation, and maintenance of these key elements. By evaluating the potential hazards associated with the introduction of hydrogen infrastructure, we identified significant risks and recommended several actions and activities to mitigate them, aiming to promote the safe use of hydrogen in transportation and ensure that the infrastructure is developed and operated with a strong emphasis on safety. This assessment will guide more detailed analyses in subsequent phases, ensuring that all stakeholders, including officials and engineers, are well-informed and prepared to manage the associated risks. Ultimately, these efforts contribute to the safe and sustainable integration of hydrogen technology, paving the way for its long-term success in the transportation sector.

CRediT authorship contribution statement

Seyed Mojtaba Hoseyni: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mohamed Osman Mesbah Mostafa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joan Cordiner:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization.

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.

References

[1] Shaterabadi M, Sadeghi S, Jirdehi MA. The role of green hydrogen in achieving low and net-zero carbon emissions: climate change and global warming. In: Green hydrogen in power systems. Springer International Publishing; 2024. p. 141–53.
[2] Zhang D, Jiang M, Li G, Tang Y. An advanced bibliometric analysis and future research insights on safety of hydrogen energy. J Energy Storage 2024;77:109833.
[3] Amer MO, Hoseyni SM, Cordiner J. Fuelling the future with safe hydrogen transportation through natural gas pipelines: a quantitative risk assessment approach. Trans. Indian Nation. Acade. Eng. 2024:1–19.
[4] Agrawal D, Mahajan N, Singh SA, Sreedhar I. Green hydrogen production pathways for sustainable future with net zero emissions. Fuel 2024;359:130131.
[5] Hoseyni SM, Cordiner J. A novel framework for quantitative resilience assessment in complex engineering systems during early and late design stages. Process Saf Environ Protect 2024;189:612–27.
[6] Kumar S, Nanan-Surujbally A, Sharma DP, Pathak D. Hydrogen safety/standards (national and international document standards on hydrogen energy and fuel cell). In: Towards hydrogen infrastructure. Elsevier; 2024. p. 315–46.
[7] Xiao H, Li B, Yu H, Shu C-M. Dynamic risk analysis of hydrogen refueling station gas cloud explosions based upon the bow-tie perspective. Int J Hydrogen Energy 2024;82:89–101.
[8] Tamura Y, Takabayashi M, Takeuchi M. The spread of fire from adjoining vehicles to a hydrogen fuel cell vehicle. Int J Hydrogen Energy 2014;39(11):6169–75.
[9] Wang C, Wang L, Su C, Jiang M, Li Z, Deng J. Modeling and performance analysis of emergency response process for hydrogen leakage and explosion accidents. J Loss Prev Process Ind 2024;87:105239.
[10] Farhana K, Mahamude ASF, Kadirgama K. Comparing hydrogen fuel cost of production from various sources-a competitive analysis. Energy Convers Manag 2024;302:118088.
[11] Pourgol-Mohammad M, Hoseyni S, Hoseyni S, Sepanloo K. A practical sensitivity analysis method for ranking sources of uncertainty in thermal–hydraulics applications. Nucl Eng Des 2016;305:400–10.
[12] Yousefpour F, Hoseyni SM, Hoseyni SM, Hashemi Olia SA, Karimi K. Creep rupture assessment for Level-2 PSA of a 2-loop PWR: accounting for phenomenological uncertainties. Nucl Sci Tech 2017;28(8):1–9.
[13] Nakayama J, Sakamoto J, Kasai N, Shibutani T, Miyake A. Preliminary hazard identification for qualitative risk assessment on a hybrid gasoline-hydrogen fueling station with an on-site hydrogen production system using organic chemical hydride. Int J Hydrogen Energy 2016;41(18):7518–25.
[14] Suzuki T, Izato Y-i, Miyake A. Identification of accident scenarios caused by internal factors using HAZOP to assess an organic hydride hydrogen refueling station involving methylcyclohexane. J Loss Prev Process Ind 2021;71:104479.
[15] Wang X, Gao W. Hydrogen leakage risk assessment for hydrogen refueling stations. Int J Hydrogen Energy 2023;48(91):35795–808.
[16] Park B, Kim Y, Lee K, Paik S, Kang C. Risk assessment method combining independent protection layers (IPL) of layer of protection analysis (LOPA) and RISKCURVES software: case study of hydrogen refueling stations in urban areas. Energies 2021;14(3):4043.
[17] Al-Shanini A, Ahmad A, Khan F. Accident modelling and safety measure design of a hydrogen station. Int J Hydrogen Energy 2014;39(35):20362–70.
[18] Gye H-R, Seo S-K, Bach Q-V, Ha D, Lee C-J. Quantitative risk assessment of an urban hydrogen refueling station. Int J Hydrogen Energy 2019;44(2):1288–98.
[19] Zhiyong L, Xiangmin P, Jianxin M. Quantitative risk assessment on a gaseous hydrogen refueling station in Shanghai. Int J Hydrogen Energy 2010;35(13):6822–9.
[20] Yoo B-H, Wilailak S, Bae S-H, Gye H-R, Lee C-J. Comparative risk assessment of liquefied and gaseous hydrogen refueling stations. Int J Hydrogen Energy 2021;46(71):35511–24.
[21] Tsunemi K, Kihara T, Kato E, Kawamoto A, Saburi T. Quantitative risk assessment of the interior of a hydrogen refueling station considering safety barrier systems. Int J Hydrogen Energy 2019;44(41):23522–31.
[22] Kwon D, Choi SK, Yu C. Improved safety by cross analyzing quantitative risk assessment of hydrogen refueling stations. Int J Hydrogen Energy 2022;47(19):10788–98.
[23] Suzuki T, Shiota K, Izato Y-i, Komori M, Sato K, Takai Y, Ninomiya Takayuki, Miyake A. Quantitative risk assessment using a Japanese hydrogen refueling station model. Int J Hydrogen Energy 2021;46(11):8329–43.
[24] Xing Y, Wu J, Bai Y, Cai J, Zhu X. All-process risk modelling of typical accidents in urban hydrogen refueling stations. Process Saf Environ Protect 2022;166:414–29.

[25] Russo P, Marco AD, Mazzaro M, Capobianco L. Quantitative risk assessment on a hydrogen refuelling station. Chem. Eng. Trans. 2018;67:739–44.
[26] Xie Q, Zhou T, Wang C, Zhu X, Ma C, Zhang A. An integrated uncertainty analysis method for the risk assessment of hydrogen refueling stations. Reliab Eng Syst Saf 2024;248:110139.
[27] Kwak H, Kim M, Min M, Park B, Jung S. Assessing the quantitative risk of urban hydrogen refueling station in Seoul, South Korea, using SAFETI model. Energies 2024;17(4):867.
[28] Zhang X, Qiu G, Wang S, Wu J, Peng Y. Hydrogen leakage simulation and risk analysis of hydrogen fueling station in China. Sustainability 2022;14(19):12420.
[29] LaFleur AC, Muna AB, Groth KM. Application of quantitative risk assessment for performance-based permitting of hydrogen fueling stations. Int J Hydrogen Energy 2017;42(11):7529–35. 42.
[30] Sun K, Pan X, Li Z, Ma J. Risk analysis on mobile hydrogen refueling stations in Shanghai. Int J Hydrogen Energy 2014;39(35):20411–9.
[31] Zhiyong LI, Xiangmin PAN, Jianxin MA. Quantitative risk assessment on 2010 Expo hydrogen station. Int J Hydrogen Energy 2011;36(6):4079–86.
[32] Rodionov A, Wilkening H, Moretto P. Risk assessment of hydrogen explosion for private car with hydrogen-driven engine. Int J Hydrogen Energy 2011;36(3): 2398–406.
[33] Shen Y, Lv H, Hu Y, Li J, Lan H, Zhang C. Preliminary hazard identification for qualitative risk assessment on onboard hydrogen storage and supply systems of hydrogen fuel cell vehicles. Renew Energy 2023;212:834–54.
[34] Ehrhart BD, Brooks DM, Muna AB, LaFleur CB. Risk assessment of hydrogen fuel cell electric vehicles in tunnel. Fire Technol 2020;56:891–912.
[35] Al-Douri A, Ruiz-Tagle A, Groth KM. A quantitative risk assessment of hydrogen fuel cell forklifts. Int J Hydrogen Energy 2023;48(50):19340–55.
[36] Spada M, Burgherr P, Rouelle PB. Comparative risk assessment with focus on hydrogen and selected fuel cells: application to Europe. Int J Hydrogen Energy 2018;43(19):9470–81.
[37] Cui S, Zhu G, He L, Wang X, Zhang X. Analysis of the fire hazard and leakage explosion simulation of hydrogen fuel cell vehicles. Therm Sci Eng Prog 2023;41: 101754.
[38] Sun K, Li Z. Quantitative risk analysis of life safety and financial loss for road accident of fuel cell vehicle. Int J Hydrogen Energy 2019;44(17):8791–8.
[39] Han H, Kim S, Park J, Kim G, Jung S. Risk mitigation study for hydrogen releases from hydrogen fuel cell vehicles. Int J Hydrogen Energy 2024;54:1593–602.
[40] Wang F, Xiao J, Kuznetsov M, Breitung W, He B, Rui S, Zhou S, Jordan T, Song K, Zhang L. Deterministic risk assessment of hydrogen leak from a fuel cell truck in a real-scale hydrogen refueling station. Int J Hydrogen Energy 2024;50:1103–18.
[41] Song B, Wang X, Kang Y, Li H. Research on hydrogen leakage diffusion and safety analysis in hydrogen fuel cell vehicles with regard to leakage location and ventilation ports. Int J Hydrogen Energy 2024;83:173–87.
[42] Park B, Kim Y. Hwang and In-Ju, "Risk assessment of explosion accidents in hydrogen fuel-cell rooms using experimental investigations and computational fluid dynamics simulations,". Fire 2023;6(10):390.
[43] Dai J, Yang S, Yang Y, Fang Q. Research on the consequences of hydrogen leakage and explosion accidents of fuel cell vehicles in underground parking garages. Int J Hydrogen Energy 2024;77:1296–306.
[44] Zhao Q, Li Y, Cao W, Li Y. Risk analysis of high-pressure hydrogen leakage in confined space with tube skid container for cylinder. Int J Hydrogen Energy 2024; 60:581–92.
[45] Houssin-Agbomson D, Vyazmina E, Ravinel B, Bernard-Michel G. Risk assessment and mitigation evaluation for hydrogen vehicles in private garages. Experiments and Modelling; 2021.
[46] Ehrhart BD, Harris SR, Blaylock ML, Muna AB, Quong S. Risk assessment and ventilation modeling for hydrogen releases in vehicle repair garages. Int J Hydrogen Energy 2021;46(23):12429–38.
[47] Card AJ, Ward JR, Clarkson PJ. Beyond FMEA: the structured what-if technique (SWIFT). J Healthc Risk Manag 2012;31(4):23–9.
[48] IEC. Risk management – risk assessment techniques Management; IEC 31010. International Electrotechnical Commission (IEC); 2019.
[49] CCPS. Bow ties in risk management: a concept book for process safety, center for chemical process safety. Incorporated: John Wiley & Sons; 2018.
[50] UKEI. Guidelines for the management of safety critical elements. third ed. London: UK Energy Institute (EI); 2020.
[51] Hübert T, Boon-Brett L, Buttner W. Sensors for safety and process control in hydrogen technologies. CRC Press; 2018.
[52] NFPA , NFPA 2. Hydrogen technologies code. National Fire Protection Association; 2020.
[53] Gerbec M, Jovan V, Petrovčič J. Operational and safety analyses of a commercial PEMFC system. Int J Hydrogen Energy 2008;33(15):4147–60.
[54] McNay J. A guide to fire and gas detection design in hazardous industries. CRC Press; 2022.
[55] BS 60080, Explosive and toxic atmospheres. Hazard detection mapping. Guidance on the placement of permanently installed flame and gas detection devices using software tools and other techniques. London: British Standards Institution (BSI); 2020.
[56] NFPA , NFPA 72. National fire alarm and signaling code. The National Fire Protection Association; 2024.
[57] ISA. Guidance on the evaluation of fire, combustible gas and toxic gas system effectiveness. International society of automation. 2010.
[58] IEC. Explosive atmospheres - electrical installations inspection and maintenance. BSI Standards Publications; 2024.
[59] HyApproval. Handbook for hydrogen refuelling station approval. AirLiquide; 2008.
[60] UKEI. Guidance on hydrogen delivery systems for refuelling of motor vehicles, co-located with petrol fuelling stations. London: UK Energy Institute; 2017.
[61] ISO. Gaseous hydrogen — fuelling stations — Part 1: general requirements. 1 ed. ISO; 2020.
[62] Molkov V. Fundamentals of hydrogen safety engineering. Bookboon; 2012.
[63] Rigas F, Amyotte P. Hydrogen safety. first ed. CRC Press; 2012.
[64] Hajji Y, Bouteraa M, ELCafsi A, Belghith A, Bournot P, Kallel F. Natural ventilation of hydrogen during a leak in a residential garage. Renew Sustain Energy Rev 2015; 50:810–8.
[65] BS 61508. Functional safety of electrical/electronic/programmable electronic safety-related systems. British Standards Institution (BSI); 2010.
[66] API 521. Pressure-relieving and depressurising systems. American Petroleum Institute; 2022.
[67] API 526, Flanged Steel Pressure-relief Valves. API). The American Petroleum Institute; 2023.
[68] Veres J, Ochodek T, Kolonicny J. Safety aspects of hydrogen fuelling stations. Chem. Eng. Trans. 2022;91:49–54.
[69] Yoo B-H, Wilailak S, Bae S-H, Gye H-R, Lee C-J. Comparative risk assessment of liquefied and gaseous hydrogen refueling stations. Int J Hydrogen Energy 2021;46 (71):35511–24.
[70] Hirayama M, Shinozaki H, Kasai N, Otaki T. Comparative risk study of hydrogen and gasoline dispensers for vehicles. Int J Hydrogen Energy 2018;43(27): 12584–94.
[71] Saffers J-B, Molkov VV. Hydrogen safety engineering framework and elementary design safety tools. Int J Hydrogen Energy 2014;39(11):6268–85.
[72] Xie H, Li X, Christopher DM. Emergency blower ventilation to disperse hydrogen leaking from a hydrogen-fueled vehicle. Int J Hydrogen Energy 2015;40(25): 8230–8.
[73] HSE. Installation permitting guidance for hydrogen and fuel cell stationary applications. RR715. UK: Health and Safety Laboratory UK; 2009.
[74] LaFleur AC, Muna AB, Groth KM. Application of quantitative risk assessment for performance-based permitting of hydrogen fueling stations. Int J Hydrogen Energy 2017;42(11):7529–35.
[75] HSE. Control of major accident hazards regulations 2015 (COMAH). 3rd edition. UK: Health and Safety Executive; 2015. ISBN 978 0 7176 6605 8.