



Review Article

Risk Analysis in Hydrogen Supply Chains: A Systematic Review of Safety Assessment Approaches

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ABSTRACT

Hydrogen is increasingly deployed across production, storage, transport, and end-use systems, raising significant safety and risk-management challenges. This study presents a PRISMA-based systematic review of scientific and technical literature on hydrogen supply chain risk assessment methods published between 2010 and 2025, with searches completed on 20 September 2025. Using the context–intervention–mechanism–outcome framework, the review classifies and compares quantitative risk assessment, consequence modelling, safety barrier analysis, and monitoring-oriented approaches across supply chain stages. The results show a strong concentration on storage and transport applications and a predominance of static, scenario-based methodologies. Monitoring systems are generally treated as operational support tools rather than as inputs for dynamic probabilistic updating. The review identifies limitations in cross-stage integration, uncertainty treatment, and barrier-performance modelling, and highlights the need for more integrated and monitoring-informed hydrogen safety assessment frameworks.

KEYWORDS

Hydrogen supply chain; Risk assessment; Hydrogen safety; Process safety; Safety barriers; Systematic literature review.

INTRODUCTION

Hydrogen is increasingly regarded as a strategic energy carrier for supporting the transition towards low-carbon and climate-neutral energy systems [1]. The scientific and technical basis for this role has been established in foundational literature on hydrogen as an energy medium

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[2] and in recent institutional safety reviews [3]. Its relevance is particularly evident in hard-to-abate sectors such as heavy industry, long-distance transport, and large-scale energy storage, as documented in recent supply chain integration reviews [4] and process safety literature [5]. At the same time, the expansion of hydrogen technologies introduces safety challenges across the entire supply chain. Relevant studies span mobile refuelling stations [6], urban hydrogen refuelling installations [7], marine fuel applications [8], hydrogen liquefaction pathways [9], and foundational process safety frameworks [10].

Hydrogen-related hazards are linked to its physicochemical properties, including low ignition energy, wide flammability limits, and high diffusivity [11]. In some configurations, high operating pressures or cryogenic conditions introduce additional hazard modes particularly relevant to storage and transport in large-scale hydrogen deployment contexts [12]. These characteristics may contribute to scenarios such as jet fires, flash fires, and vapor cloud explosions, as documented in global hydrogen safety reviews [13], quantitative risk assessments for refuelling stations [14], and safety management integration studies [15]. More severe consequences, including blast-wave effects and boiling liquid expanding vapour explosion phenomena, have been characterised for compressed and liquefied hydrogen systems, as documented in early blast-wave studies [16] and more recent BLEVE analyses [17][18]. Over the past decades, hydrogen safety has been analysed using quantitative risk assessment, numerical consequence modelling, experimental testing, and standards- or regulation-oriented safety analyses [19][20].

Despite the substantial volume of hydrogen safety literature, existing review works often concentrate on specific components, selected accident scenarios, or individual analytical techniques [21]. As a result, the way safety and risk assessment methods are distributed across different stages of the hydrogen supply chain remains insufficiently synthesized [22]. In particular, the relationships among analytical models, safety barrier concepts, and monitoring functions are rarely examined within a unified framework spanning the full chain. Policy documents such as the REPowerEU progress assessment [23] and the European Hydrogen Backbone report [24] confirm this structural gap from an infrastructure planning perspective.

A recurring limitation is that monitoring is frequently treated as a detection-and-response support function, while risk models remain static and scenario-based [19]. Probabilistic frequency analyses [25] and dynamic risk modelling frameworks [26] have specifically highlighted this limitation. Operational information such as gas detection, condition monitoring, or diagnostic signals is only rarely used to update scenario likelihoods or barrier performance assumptions [25][26]. This gap is also evident in industry deployment initiatives that fall outside the academic literature [27]. To address this gap, the present study conducts a PRISMA-based systematic literature review, operationalized through the context–intervention–mechanism–outcome framework, in order to map and compare safety assessment approaches across hydrogen supply chain stages and identify pathways for stronger integration between monitoring and risk modelling.

The objective of this review is therefore twofold: first, to provide a structured synthesis of the scientific and technical literature on hydrogen supply chain risk assessment; second, to clarify where current approaches remain fragmented and where future research can support more coherent, monitoring-informed hydrogen safety management, as called for by methodological reviews [19], comprehensive hydrogen safety surveys [21], and dynamic risk assessment studies [26].

Recent developments have intensified both the deployment of hydrogen infrastructure and the urgency of advancing safety assessment methodologies. The accelerating expansion of renewable hydrogen production, the emergence of large-scale hydrogen valleys, and the integration of hydrogen into national energy strategies have brought renewed attention to supply chain safety [28]. At the same time, recent reviews have confirmed that the literature remains fragmented along methodological and sectoral lines, with limited cross-stage integration and insufficient treatment of dynamic risk conditions [29]. New contributions have

addressed socio-technical dimensions of safety barriers [30] and the climate implications of hydrogen leakage across infrastructure systems [31], highlighting the broadening scope of hydrogen safety research. Optimization studies increasingly incorporate uncertainty in supply chain modelling [32], yet the coupling of logistics-oriented frameworks with process safety variables remains underexplored. These advances confirm that while the field is progressing, a consolidated and monitoring-informed synthesis of safety assessment methods across the hydrogen supply chain is both timely and necessary [33].

MATERIALS AND METHODS

This study adopts a systematic literature review methodology to analyse safety and risk assessment approaches applied to hydrogen supply chains. The methodological design draws on established process safety frameworks [34], recent comprehensive reviews of hydrogen risk analysis [19], and systematic review practices in hydrogen energy systems research [20]. The review protocol was designed to ensure transparency, reproducibility and methodological consistency, following principles commonly adopted in PRISMA-oriented review studies and evidence synthesis methodologies. The corpus includes peer-reviewed scientific literature together with selected technical and grey literature directly relevant to hydrogen safety, standards, infrastructure deployment or risk-assessment practice.

Data sources

Peer-reviewed scientific articles were retrieved from Scopus and Web of Science, which provide broad coverage of engineering, energy and safety-related literature. Google Scholar was used as a complementary source to identify additional potentially relevant studies for screening and to support targeted checking of technical literature. The use of multiple databases is consistent with systematic review practices in hydrogen safety and energy systems research [21], including recent reviews addressing hydrogen supply chain integration [4] and specific domains such as marine fuel applications [8].

Search strategy

Searches were performed on title, abstract and keywords where supported. The main temporal coverage for database searching spanned 2010–2025 (inclusive), corresponding to the rapid expansion phase of hydrogen technologies and related safety research [34]. Earlier foundational works were retained only when they were required to support technical background, hazard interpretation or established process-safety terminology. Only studies published in English were considered. Searches were executed on 20 September 2025.

The search strategy combined keywords associated with hydrogen supply chains, storage, refuelling stations, pipelines, compression, liquefaction, quantitative risk assessment, consequence modelling, leak and release scenarios, monitoring systems, safety barriers, fire, explosion, BLEVE and hydrogen infrastructure safety [19][25][26]. Boolean operators and truncation functions were used to improve retrieval consistency across databases. Table 1 reports the query strings used and the target fields.

Table 1: Search queries, target fields, and time window.

Database	Exact query string	Time window
Scopus	TITLE-ABS-KEY(("hydrogen" OR "H2" OR "LH2") AND ("supply chain" OR "logistics" OR "transport*" OR "distribution" OR "storage" OR "refuelling" OR "refueling" OR "pipeline" OR "tank" OR "compression" OR "liquefaction") AND ("risk" OR "risk analysis" OR "safety" OR "hazard") AND ("quantitative risk assessment" OR "consequence" OR "barrier*" OR "monitor*" OR "CFD" OR "leak*" OR "release" OR "fire" OR "explosion" OR "BLEVE"))	2010–2025
Web of Science	TS=(("hydrogen" OR "H2" OR "LH2") AND ("supply chain" OR "logistics" OR "transport*" OR "distribution" OR "storage" OR "refuelling" OR "refueling" OR "pipeline" OR "tank" OR "compression" OR "liquefaction") AND ("risk" OR "risk analysis" OR "safety" OR "hazard") AND ("quantitative risk assessment" OR "consequence" OR "barrier*" OR "monitor*" OR "CFD" OR "leak*" OR "release" OR "fire" OR "explosion" OR "BLEVE"))	2010–2025
Google Scholar (screening)	"hydrogen" safety risk supply chain storage transport refuelling station leakage release explosion fire consequence monitoring barrier CFD BLEVE	2010–2025

Inclusion and exclusion criteria

Studies were included in the PRISMA set if they met all of the following criteria:

- peer-reviewed journal articles, or grey literature with direct relevance to hydrogen safety policy, infrastructure deployment, or technical standards (including institutional reports, regulatory roadmaps, and normative documents);
- explicit focus on hydrogen-related safety or risk assessment;
- application of qualitative, semi-quantitative or quantitative risk analysis methods, or safety-relevant modelling;
- relevance to at least one hydrogen supply chain stage: production, conditioning, compression, liquefaction, storage, transport, distribution or end-use. This scope encompasses supply chain integration perspectives [4], refuelling station analyses [6][7], liquefaction systems [9], and foundational process safety references [10].

Studies were excluded if they:

- were grey literature without a direct hydrogen safety or risk assessment dimension (e.g. purely economic or commercial documents with no technical safety content);
- addressed hydrogen solely from economic, environmental or policy perspectives without an explicit safety dimension;
- lacked sufficient methodological detail to support comparison and classification, following criteria applied in supply chain safety reviews [4], comprehensive hydrogen safety analyses [21], and recent evidence syntheses [29].

Accordingly, the PRISMA set includes peer-reviewed journal articles and grey literature (institutional reports, technical standards, regulatory roadmaps, and normative documents) published or released mainly between 2010 and 2025 that perform, support, or contextualise safety or risk assessment for at least one hydrogen supply chain stage. Earlier foundational sources were used only where they provided necessary technical background. The inclusion criteria were designed to ensure methodological comparability across sources employing quantitative risk assessment, computational consequence modelling, probabilistic approaches, monitoring systems or safety barrier analyses. This scope aligns with the methodological coverage of refuelling station risk assessments [6][7], hydrogen risk analysis reviews [19], and monitoring-informed probabilistic approaches [25][26].

Screening process

Study selection followed PRISMA principles to improve transparency and reproducibility of the review process. After duplicate removal, titles and abstracts were screened, followed by full-text assessment based on the eligibility criteria. Sources not explicitly addressing hydrogen safety assessment or lacking sufficient methodological detail were excluded during full-text evaluation, applying criteria consistent with hydrogen safety methodology reviews [19], safety challenge surveys [21], and recent evidence syntheses [29]. The PRISMA flow diagram is provided in Figure 1.

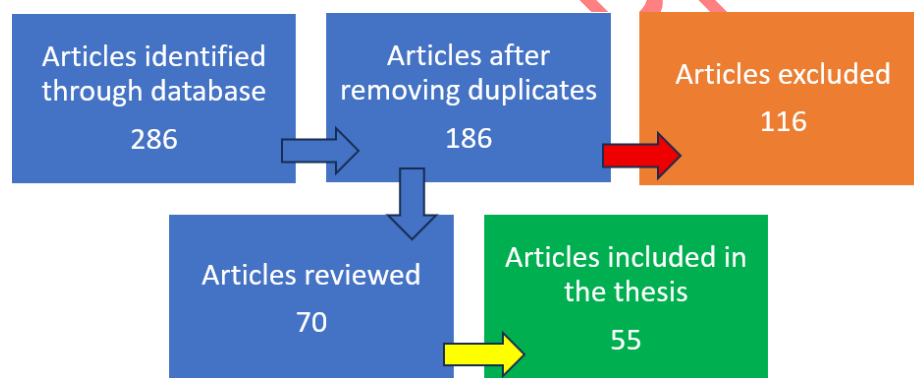


Figure 1: PRISMA flow diagram illustrating study identification, screening, eligibility assessment, and inclusion. Sources included in the PRISMA review: N = 55.

Data extraction and classification

The selected studies were classified using the context–intervention–mechanism–outcome (CIMO) framework. For each included work, the following items were extracted:

- Context: supply chain stage(s), physical system and operational setting;
- Intervention: safety and risk assessment approach;
- Mechanism: analytical linkage used to connect hazards to outputs;
- Outcome: reported outputs and decision metrics.

A structured mapping of representative studies according to the context–intervention–mechanism–outcome (CIMO) dimensions is provided in Appendix A (Table A1) to improve transparency and reproducibility of the classification process.

Data availability and reproducibility

This article is a systematic review. No new experimental or field data were generated. The review protocol, eligibility criteria and classification logic support reproducibility of the study.

Mathematical formulation of risk metrics

The reviewed studies commonly express risk as a combination of scenario likelihood and consequence severity. This formulation draws on probabilistic frameworks from process safety literature [5] and is applied in hydrogen-specific risk methodologies [19][20]:

$$R = \sum_{i=1}^N P_i \cdot C_i \quad (1)$$

where P_i denotes the probability of occurrence of scenario i and C_i represents the associated consequence measure [34][20]. This probabilistic formulation is widely adopted

in quantitative risk assessment studies addressing hydrogen releases and storage failures [35], transport-related accident scenarios including liquid hydrogen tank safety [36], and materials hydrogen compatibility analyses [37].

In many applications, the influence of safety barriers is represented through multiplicative reduction factors acting on the probability of occurrence and/or the magnitude of consequences [38][39]. Such approaches are commonly used to represent the preventive and mitigative effectiveness of engineered and operational safety barriers, including emergency shutdown systems, pressure relief devices, ventilation systems and monitoring-based response mechanisms [38][39].

$$R = \sum_{i=1}^N P_i \cdot \alpha_i \cdot C_i \cdot \beta_i \quad (2)$$

where $\alpha_i \in [0,1]$ represents the preventive effectiveness of safety barriers for scenario i , while $\beta_i \in [0,1]$ represents the corresponding mitigative effectiveness. Similar formulations are frequently adopted in hydrogen safety studies to account for the influence of technical barriers, operational procedures and monitoring systems on accident prevention and consequence mitigation [38][39].

In the present conceptual formulation, α_i and β_i are treated as adjustable scalar parameters representing barrier effectiveness. However, future monitoring-informed implementations may model these parameters probabilistically in order to account for uncertainty, degradation effects and time-dependent operational variability.

RESULTS

This section reports the results of the PRISMA-based systematic review on risk analysis in hydrogen supply chains, based on the included scientific and technical sources ($N = 55$). Results are reported descriptively, while interpretative synthesis is provided in the Discussion. The analysed literature includes sources focused on quantitative risk assessment, consequence modelling, safety barrier evaluation, computational fluid dynamics and monitoring-informed safety approaches applied to hydrogen systems, drawing on risk analysis methodologies [19][20] and comprehensive hydrogen safety challenge reviews [21].

Distribution of studies along the hydrogen supply chain

The included sources address hydrogen safety across multiple stages of the supply chain, including production, liquefaction, storage, transportation, distribution and end-use applications. This coverage spans supply chain integration reviews [4], refuelling station assessments [6][7], marine fuel studies [8], and liquefaction pathway analyses [9]. Each source was assigned to the relevant supply-chain stage based on the main system, scenario or analytical focus considered.

The review indicates that storage and transport systems represent the most frequently investigated stages, mainly due to the elevated pressures and cryogenic conditions associated with hydrogen handling infrastructures [9]. Research on advanced solid-state hydrogen storage materials, including metal hydrides based on severe plastic deformation techniques, further broadens this focus [40]. Global hydrogen reviews confirm the centrality of these stages [13], as do quantitative risk studies at refuelling stations [14] and blast-wave analyses for high-pressure vessels [35][36]. Several studies also focus on accidental release scenarios, vapor cloud dispersion, jet fires, and BLEVE phenomena involving compressed or liquefied hydrogen systems. This includes analyses of natural hydrogen well safety [41], mechanical energy release in tank rupture [42], and loss of integrity in hydrogen technologies [43].

Table 2 reports the distribution of included sources by supply chain stage. Because some sources address more than one stage, the categories are reported as primary or secondary analytical foci and are not mutually exclusive.

Table 2: Distribution of included sources by hydrogen supply chain stage. Percentages are calculated over the total corpus of reviewed studies ($N = 55$) and may exceed 100% because categories are not mutually exclusive and some studies address multiple supply-chain stages.

Supply chain stage	Number of sources (n)	Share [%]
Production	8	14.5
Compression / liquefaction / conditioning	8	14.5
Storage (gaseous / cryogenic)	20	36.4
Transport / distribution	13	23.6
End-use applications	8	14.5

Risk types and analytical approaches

Across the included literature, the analysed hazardous scenarios primarily involve unintended hydrogen releases and their potential consequences. These include dispersion of flammable clouds, jet fires, and flash fires driven by the physicochemical properties of hydrogen [11], as well as thermal radiation effects and blast-wave overpressure phenomena associated with high-pressure or cryogenic system failures. Relevant analyses include liquid hydrogen BLEVE modelling [17][18], blast-wave characterisation for high-pressure tanks [35], mechanical energy release studies [42], and loss-of-integrity investigations [43].

Quantitative risk assessment and consequence modelling emerge as the dominant analytical approaches across the PRISMA set. This pattern is consistent across refuelling station assessments [6][7], cross-station safety comparisons [14], and methodological reviews of hydrogen risk analysis [19][20]. Probabilistic methods are commonly used to estimate accident frequencies, individual risk and societal risk indicators, while computational fluid dynamics and thermodynamic models are employed to simulate hydrogen dispersion, thermal effects and blast overpressure distributions, as demonstrated in liquid hydrogen BLEVE analyses [17], high-pressure tank rupture studies [35], and mechanical energy release investigations [42].

More recent contributions also integrate monitoring systems, sensor fusion and predictive safety analytics into hydrogen infrastructure safety management frameworks [25][26].

Table 3 summarizes the most recurrent methodological families observed across the reviewed literature and the corresponding types of outputs reported. The classification is intentionally non-exhaustive and focuses on dominant analytical approaches. Several studies adopt hybrid, cross-cutting or narrative perspectives and therefore were not uniquely assigned to a single methodological category.

Table 3: Recurring risk assessment methodological families observed in the reviewed literature. Note: categories are representative of dominant methodological approaches and are not mutually exclusive; several studies employ hybrid or narrative approaches and therefore are not uniquely classified. Counts do not sum to $N = 55$.

Methodological approach	Representative works (n)	Typical reported outputs
Quantitative risk assessment	7	Individual and societal risk indicators; frequency–consequence metrics; risk acceptability metrics
Consequence modelling (CFD)	6	Dispersion fields; thermal radiation maps; overpressure estimates; impact distances
Hybrid probabilistic and consequence modelling	5	Scenario-based metrics combining probabilistic and numerical modelling
Monitoring-informed and data-oriented approaches	4	Predictive indicators; detection logic; monitoring-to-decision support links

Representation of monitoring and mitigation measures

Mitigation measures discussed in the included sources include passive and active safety provisions such as pressure relief devices, containment systems, safety distances, ventilation strategies, emergency shutdown systems and procedural controls. These measures are addressed in functional safety standards [38], hydrogen safety guidelines [39], energy transition outlook reports [44], and European hydrogen infrastructure roadmaps [45]. Several contributions also analyse engineered safety barriers for hydrogen storage and transport systems, particularly in relation to high-pressure vessels and cryogenic infrastructures, as examined in refuelling station cross-analyses [14], high-pressure tank rupture studies [35], mechanical energy release investigations [42], and loss-of-integrity analyses [43].

Monitoring is represented primarily through hydrogen detection systems, condition monitoring and alarm or response mechanisms [25][26]. Recent studies emphasize the increasing adoption of sensor fusion, Internet of Things-based architectures and predictive analytics for hydrogen infrastructure safety management. Representative contributions address CCS project safety [46], comparative risk assessment of formic acid versus gaseous hydrogen stations [47], resilience-assuring microgrid architectures [48], quantitative risk assessment using a Japanese refuelling station model [49], optimisation of renewable hydrogen systems [50], hydrogen leakage risk assessment [51], comparative station analyses [52], and advanced hydrogen storage materials including high-entropy hydrides [53]. Across the PRISMA set, monitoring functions are usually described as inputs to safety systems or as supporting elements within risk scenarios, rather than as dynamic variables capable of continuously

updating probabilistic risk indicators, as observed in risk methodology reviews [19], Bayesian leak frequency analyses [25], and dynamic risk frameworks [26].

DISCUSSION

The evidence mapped in this review highlights several recurring patterns and limitations in current hydrogen supply chain risk assessment practices. A first observation concerns the predominance of component-level analyses within the reviewed literature, a pattern identified across methodological reviews of hydrogen risk analysis [19], systematic safety assessments [20], and comprehensive hydrogen safety challenge surveys [21]. Storage and transport systems are the most frequently investigated stages, reflecting their association with high energy densities, elevated operating pressures and potentially severe accident consequences associated with cross-station analyses [14], blast-wave characterisation [35], and mechanical energy release studies [42]. While this focus is technically justified, it implies that interactions among multiple supply chain stages are often underexplored, particularly with respect to cross-stage dependencies and potential cascading effects [4]. This gap persists even in supply chain optimisation studies that already incorporate uncertainty [32][33]. The reviewed literature shows that hydrogen safety assessment remains largely dominated by component-level and scenario-specific analyses [19][20], a finding corroborated by comprehensive hydrogen safety surveys [21]. In most cases, analytical methods are applied to discrete systems such as storage tanks, pipelines, refuelling installations or production units, rather than to strongly coupled supply chain configurations. This pattern is observed across Korean mobile refuelling station assessments [6][7], cross-station comparisons [14], and safety management integration studies for production facilities [15].

At a conceptual level, the evidence suggests three recurring layers of safety assessment. The first layer concerns hazard identification and scenario definition, including releases, ignition outcomes, thermal effects and overpressure consequences associated with hydrogen physicochemical properties [11], BLEVE events [17], and high-pressure tank ruptures [35]. The second layer concerns analytical treatment through probabilistic methods [6][7], consequence modelling, or hybrid approaches that draw on established hydrogen risk assessment methodologies [19][20]. The third layer concerns the representation of safety barriers and monitoring functions, which may prevent accident initiation, reduce escalation, or support emergency response, as framed in socio-technical safety barrier analyses [30] and reflected in functional safety standards [38][39].

A key pattern emerging from the review is that monitoring is most often represented as an operational safety function rather than as a formal input for dynamic risk updating [19]. This limitation has been highlighted in Bayesian frequency analyses [25] and dynamic risk modelling frameworks [26]. In practical terms, monitoring is mainly used for detection, alarm generation and response activation, while it is only rarely used to revise scenario likelihoods, barrier performance assumptions or risk indicators in near real time [25][26]. This limitation is particularly relevant for emerging hydrogen infrastructures characterized by variable operating conditions and evolving system configurations [4], particularly in the context of expanding European hydrogen networks [23][24].

This conceptual interpretation supports the view that future progress in hydrogen supply chain safety research will depend not only on improved hazard modelling, but also on stronger integration between probabilistic assessment [19], barrier performance representation, and monitoring-based information flows [25][26].

Quantitative risk assessment and computational consequence modelling emerge as the two dominant methodological approaches. Refuelling station risk assessments [6][7] and cross-station safety analyses [14] exemplify the quantitative approach, while methodological reviews

confirm its dominance across the literature [19][20]. Probabilistic frameworks are widely used to estimate individual and societal risk metrics, while consequence models provide detailed representation of dispersion, thermal radiation, and overpressure effects, as demonstrated in liquid hydrogen BLEVE analyses [17], high-pressure tank rupture studies [35], and mechanical energy release investigations [42]. However, many applications rely on static assumptions and predefined scenarios, which limits their ability to represent time-dependent operational conditions and evolving system configurations [19][26].

Uncertainty treatment remains heterogeneous across the literature [19][29]. This includes hydrogen supply chain optimisation studies, which have increasingly acknowledged uncertainty explicitly [32]. Failure probabilities and consequence parameters are often derived from historical databases, empirical correlations, or conservative assumptions [6][7]. Bayesian frequency analyses have attempted to refine these estimates using operational data [25]. Explicit differentiation between aleatory and epistemic uncertainty is rarely formalized, particularly in emerging hydrogen applications where operational data are limited [19][26].

Critical evaluation of current approaches

Although quantitative risk assessment and consequence modelling dominate the current hydrogen safety literature, most available approaches remain fragmented and strongly scenario-dependent, as evident in refuelling station studies [6][7] and confirmed by methodological reviews [19][20]. Existing studies frequently focus on isolated infrastructures such as storage tanks, pipelines, liquefaction systems or refuelling stations rather than integrated hydrogen supply chain configurations. This gap persists in supply chain reviews [4], refuelling station analyses [14], and safety management integration studies [15].

Several methodological limitations emerge from the reviewed literature.

First, many quantitative risk assessment studies rely on static assumptions and predefined accident frequencies, which may not adequately represent evolving operational conditions or maintenance degradation [6][7]. This limitation has been recognised in methodological reviews of hydrogen risk analysis [19]. Dynamic quantitative risk assessment approaches have been proposed in recent years; however, their industrial validation and integration with operational monitoring systems remain limited [26].

Second, computational fluid dynamics and BLEVE-oriented studies provide highly detailed representations of hydrogen dispersion, thermal radiation, and blast overpressure phenomena. Recent contributions have specifically characterised liquid hydrogen BLEVE mechanisms [17] and their multi-peak blast-wave structures [18]. Although authored by the same research group, these studies address different aspects of liquid hydrogen BLEVE behaviour: the former focuses on explosion mechanisms following storage tank rupture, whereas the latter analyses the resulting blast-wave structure and overpressure characteristics. Earlier work also established blast-wave characterisation for high-pressure tanks [35]. Nevertheless, these approaches are often disconnected from operational decision-making frameworks and supply chain optimization models. Advanced physical simulations improve the understanding of accident mechanisms, but they rarely support real-time safety prioritization or adaptive risk management.

Third, optimization-oriented studies addressing hydrogen logistics and infrastructure planning frequently prioritize economic efficiency and network performance while underrepresenting safety barriers [4], supply chain uncertainty [32][33], and monitoring reliability constraints [50]. This separation between operational optimization and process safety management limits the development of integrated safety-oriented hydrogen infrastructures.

Another critical issue concerns uncertainty treatment. Failure probabilities and consequence parameters are commonly derived from historical accident databases, empirical correlations, or conservative assumptions [6][7]. Bayesian approaches have sought to quantify

uncertainty in leak frequency more rigorously [25]. However, explicit differentiation between aleatory and epistemic uncertainty is rarely formalized, particularly in emerging hydrogen applications where operational datasets remain incomplete, as noted in methodological reviews [19], dynamic risk modelling studies [26], and recent evidence syntheses [29].

A further limitation concerns the representation of monitoring systems. Most reviewed studies treat monitoring as an auxiliary operational support function dedicated to leak detection and alarm activation [25][26]. This operational framing is evident even in leakage risk assessment studies that integrate sensor data [51]. Only a limited number of approaches integrate sensor-based information into probabilistic risk updating or barrier-performance evaluation frameworks [25][26].

These limitations indicate that future hydrogen safety research should move towards integrated and monitoring-informed methodologies capable of combining:

- probabilistic risk assessment;
- dynamic monitoring architectures;
- safety barrier modelling;
- uncertainty quantification and cross-stage supply chain analysis.

Such integration may support more adaptive, resilient and decision-oriented hydrogen safety management frameworks for large-scale energy infrastructures [4], in line with the ambitions of European hydrogen network programmes [23][24].

The critical comparison of selected recent studies further highlights the methodological fragmentation currently characterizing hydrogen safety assessment research. Table 4 summarizes representative contributions identified in the reviewed literature, together with their main strengths, limitations and unresolved research gaps.

Table 4: Critical comparison of recent hydrogen safety assessment approaches.

Study	Main contribution	Main limitation	Identified research gap
Cirrone et al. (2025) [54]	Advanced modelling of liquid hydrogen BLEVE blast-wave structures	Limited integration with operational safety management frameworks	Real-time decision-support integration
Zarei et al. (2021) [26]	Dynamic risk modelling for hydrogen infrastructures	Limited industrial-scale validation	Monitoring-informed probabilistic updating
Shi et al. (2020) [19]	Methodological improvements in hydrogen risk analysis	Predominantly theoretical implementation	Integration with operational monitoring systems
Subedi et al. (2025) [30]	Socio-technical interpretation of safety barriers	Limited quantitative barrier-performance modelling	Dynamic barrier effectiveness assessment
Li et al. (2025) [4]	Review of hydrogen supply chain integration and logistics	Limited representation of safety interactions	Safety-oriented supply chain optimization
Zhang et al. (2025) [32]	Optimization of hydrogen supply chains under uncertainty	Weak integration of process safety variables	Joint optimization-risk assessment frameworks
Kim et al. (2022) [6]	Quantitative risk assessment for hydrogen refuelling stations	Scenario-specific and static assumptions	Time-dependent and adaptive QRA models
Yuan et al. (2022) [55]	Numerical simulation of hydrogen leakage and explosion scenarios	Limited coupling with probabilistic approaches	Integrated CFD-probabilistic methodologies

The comparison reported in Table 4 confirms that most current approaches remain specialized on individual methodological dimensions, such as consequence modelling, optimization or safety barrier analysis. Fully integrated frameworks combining probabilistic assessment, monitoring systems, uncertainty treatment and cross-stage supply chain interactions remain limited within the current literature. This fragmentation suggests the need for more adaptive and monitoring-informed hydrogen safety assessment methodologies capable of supporting real-time decision-making across interconnected infrastructures.

Temporal evolution and methodological quality assessment

The temporal distribution of the reviewed literature reveals a progressive shift in analytical focus. Early studies (2010–2015) concentrate mainly on consequence modelling and deterministic approaches, often adapted from conventional process safety frameworks. This pattern is consistent with a phase in which hydrogen applications were less mature and the analytical priority was to establish baseline hazard understanding, particularly for high-pressure storage and transport scenarios where previous operational experience was limited. This phase drew on foundational process safety frameworks [34], blast-wave modelling for high-pressure vessels [35], and early studies on liquid hydrogen tank safety [36].

During the period 2016–2020, the literature shows greater methodological maturity. Probabilistic risk assessment becomes more widespread, with explicit attempts to quantify individual and societal risk indicators. Some works incorporate sensitivity analyses and parametric studies, although uncertainty treatment remains inconsistent. A persistent limitation during this phase is the limited availability of operational feedback, since many probability estimates rely on generic databases or engineering judgement rather than field data from hydrogen installations, as acknowledged in refuelling station risk studies [7], methodological reviews [19], and Bayesian frequency analyses [25].

More recent contributions (2021–2025) indicate a transition towards integrated and monitoring-informed approaches. This includes dynamic risk frameworks, Bayesian updating techniques and increasing interest in sensor-based safety architectures. Nevertheless, full integration remains limited: monitoring systems, barrier models and probabilistic assessments are often discussed in parallel but are seldom combined within a single coherent analytical structure. The literature therefore remains fragmented along methodological lines, a conclusion supported by dynamic risk modelling studies [26], recent evidence syntheses [29], and socio-technical safety barrier analyses [30].

From a quality standpoint, the reviewed works vary considerably in analytical depth and validation rigour. A subset of studies provides comprehensive uncertainty quantification, clearly distinguishing between aleatory and epistemic sources; others rely on point estimates without sensitivity analysis. Similarly, some works validate their models against experimental data or accident records, while others remain purely theoretical. This heterogeneity makes direct comparison difficult and limits the possibility of conducting meta-analyses or pooling results across studies.

One recurring pattern concerns the treatment of safety barriers. Earlier studies often represent barriers as simple reduction factors applied to frequency or consequence terms, without considering degradation, testing intervals or performance dependencies. More recent approaches attempt to model barrier reliability explicitly, sometimes through fault tree analysis or Markov models. Yet even these advanced representations rarely account for time-dependent degradation or for the feedback between monitoring data and barrier performance estimates. As a result, the assumed effectiveness of a barrier at $t = 0$ is often held constant throughout the analysis, even when operational data may indicate changes in its actual state, a limitation highlighted in socio-technical safety analyses [30] and reflected in functional safety standards [38][39].

Geographic distribution is another relevant source of heterogeneity. The majority of quantitative risk assessment studies focus on refuelling stations, industrial hydrogen facilities or transport corridors in Europe, Asia and North America. Coverage of emerging hydrogen economies in other regions is limited. This may introduce contextual bias, because regulatory requirements, operating practices and infrastructure maturity vary significantly across regions, and results from one setting may not transfer directly to another, as the scope and assumptions of refuelling station risk assessments vary considerably across regions, as demonstrated by Korean mobile station studies [6], urban refuelling station analyses [7], and cross-station safety comparisons [14].

Table 5: Geographic distribution of the reviewed literature (N = 55). Regional classification is based on the primary study context or geographical setting of hydrogen infrastructure and risk assessment application.

Region	Number of studies
Europe	21
Asia	16
North America	9
Multi-regional / global	6
Other regions	3

Table 5 provides a descriptive overview of the geographical distribution of the reviewed studies. Europe, Asia and North America account for the majority of contributions, reflecting greater infrastructure maturity, regulatory development and industrial deployment of hydrogen systems in these regions. The limited representation of other geographical contexts suggests that current evidence may not be fully transferable across emerging hydrogen economies with different regulatory and operational conditions.

Towards a monitoring-informed dynamic risk framework

The findings discussed above indicate that current hydrogen safety assessment remains largely decoupled from real-time operational information. Many quantitative risk models are developed with fixed parameters and are then used to evaluate scenarios or compare design alternatives. Unless these parameters are periodically updated, the model may diverge from actual plant conditions, including sensor readings, maintenance records, inspection results and operational deviations [19]. This gap has been highlighted in Bayesian frequency analyses [25] and dynamic risk modelling studies [26].

A monitoring-informed dynamic risk framework can be conceptualized through four interacting layers. The first layer is the sensor layer, including gas detectors, pressure transducers, temperature monitors and vibration sensors, which provide continuous operational data streams. The second layer is data fusion and interpretation, which combines signals, filters noise, detects anomalies and identifies patterns that may indicate degradation or precursor events. The third layer is probabilistic updating, in which interpreted information is used to revise estimates of failure probabilities, barrier performance or scenario likelihoods. The fourth layer is decision support, which translates the updated risk picture into inspection priorities, maintenance scheduling and operational adjustments [25][26].

Mathematically, this perspective requires a time-dependent risk formulation. Instead of computing risk as a static sum over scenarios, risk can be represented as $R(t)$, a quantity that evolves as new evidence becomes available. Bayesian updating provides a suitable framework for this purpose. A prior distribution for a failure-rate parameter λ can be updated as operational

data accumulate; the resulting posterior distribution can then feed back into the risk calculation and adjust scenario probabilities accordingly [25][26].

The same logic applies to barrier performance. A pressure relief device may have a nominal reliability, but that reliability can degrade over time or under harsh operating conditions. If monitoring data indicate abnormal pressure fluctuations or if inspection reveals corrosion, the effective availability $\alpha_i(t)$ should be revised downward. Conversely, successful testing or replacement may justify an upward revision. Incorporating this time dependence requires a transition from static to dynamic barrier models, as called for by socio-technical safety analyses [30] and implied by the performance requirements of functional safety standards [38][39].

For example, a hydrogen refuelling station equipped with multi-point gas detection could be represented using an evidence-updating approach. Under normal operation, a baseline leak frequency may be estimated from historical data as $\lambda_0 = 1 \times 10^{-4}$ per year. If the station operates for an extended period without detected leaks, a Poisson-Gamma updating scheme would reduce the posterior mean of the leak-frequency parameter. Conversely, minor hydrogen detections or repeated valve-maintenance issues would increase the posterior mean and indicate the need for preventive action [25][26].

Several practical challenges must be considered before such approaches can be implemented. Sensor data may be noisy, incomplete or contradictory; distinguishing genuine precursors from false alarms requires robust algorithms and domain expertise. Continuous updating may also create computational burdens when consequence models are complex. In addition, organizational integration is required so that safety engineers, data scientists and operations personnel can interpret updated risk information within a shared decision-making workflow.

As hydrogen systems scale up and operational datasets expand, static risk assessments may become progressively less adequate. The gap between assumed and actual system performance can widen if models are not updated with evidence. Monitoring-informed dynamic risk assessment therefore represents an evolution of existing methods, rather than a replacement, by making more systematic use of operational information already collected by hydrogen infrastructures [25][26], building towards the socio-technical integration of safety barriers [30].

Methodological implications

From a methodological perspective, several directions for future research can be identified, building on hydrogen risk methodology reviews [19][20] and recent evidence syntheses [29]:

- integration of monitoring data into probabilistic models, for example through Bayesian updating approaches and monitoring-informed dynamic risk assessment frameworks [25][26];
- explicit separation and reporting of different types of uncertainty, particularly aleatory and epistemic uncertainty in emerging hydrogen infrastructures, which remain undercharacterised despite advances in dynamic risk modelling [19][26] and recent evidence syntheses [29];
- development of cross-stage modelling approaches capable of capturing interdependencies and cascading effects along the hydrogen supply chain [4], building on optimisation studies that already incorporate cross-chain uncertainty [32][33];
- improved consistency in the representation of safety barriers and their influence on probabilistic risk metrics and accident mitigation performance, integrating socio-technical barrier analyses [30] with functional safety standards [38][39].

Additional research opportunities also emerge in relation to digitalization and predictive safety management. Recent studies suggest that sensor fusion, Internet of Things architectures and artificial intelligence-based diagnostics may support more adaptive and resilient hydrogen safety systems [25][26]. Leakage risk assessment studies have begun to incorporate sensor-based data towards this end [51]. However, these technologies remain only partially integrated into existing quantitative risk assessment methodologies.

These aspects suggest that future progress in hydrogen safety assessment will depend not only on improved hazard modelling, but also on stronger integration between analytical risk models, barrier performance [19], and monitoring-based information flows [25][26]. Such integration may contribute to the development of more dynamic, monitoring-informed and decision-oriented safety management frameworks for complex hydrogen supply chain infrastructures [4], in support of the expanding European hydrogen networks [23][24].

CONCLUSIONS

This paper presented a PRISMA-based systematic literature review of risk analysis approaches applied to hydrogen supply chains, structured through the context–intervention–mechanism–outcome framework, following methodological directions established in hydrogen risk analysis reviews [19][20] and recent evidence syntheses [29]. The reviewed literature indicates a strong predominance of quantitative risk assessment and consequence modelling approaches, particularly for storage and transport systems, as reflected in refuelling station assessments [6][7], cross-station safety analyses [14], and blast-wave studies [35][42]. Cross-stage integration across hydrogen supply chains remains limited [4][32].

The analysis further highlights that current hydrogen safety assessment methods remain largely static and scenario-based [19][20], with monitoring systems primarily treated as operational support functions rather than as inputs for dynamic probabilistic updating [25][26]. In addition, uncertainty treatment and safety barrier representation remain heterogeneous across the literature, particularly in relation to time-dependent operational conditions and interconnected infrastructure configurations [19][26][30].

Future research should focus on integrating monitoring data into probabilistic risk models [25][26], improving uncertainty representation, and developing cross-stage analytical approaches capable of supporting more adaptive and monitoring-informed hydrogen safety management [4][32]. The structured review and classification approach proposed in this study provide a reproducible basis for future research on integrated hydrogen supply chain safety assessment [19][20][29].

AUTHOR CONTRIBUTIONS

Conceptualization, D.I. and M.D.N.; methodology, D.I.; investigation, D.I.; data curation, D.I.; writing—original draft preparation, D.I.; writing—review and editing, D.I. and M.D.N.; supervision, M.D.N. All authors have read and agreed to the published version of the manuscript

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

NOMENCLATURE

Symbol	Description	Unit
R	risk	—
P_i	probability of occurrence of scenario i	—
C_i	consequence associated with scenario i	—
α_i	preventive effectiveness	—
β_i	mitigative effectiveness	—

REFERENCES

- [1] European Commission, A Hydrogen Strategy for a Climate-Neutral Europe, Brussels, Belgium, 2020.
- [2] Züttel, A., Borgschulte, A. and Schlapbach, L., Hydrogen as a Future Energy Carrier, Wiley-VCH, Weinheim, Germany, 2010.
- [3] U.S. Department of Energy/National Energy Technology Laboratory (DOE/NETL), Hydrogen Safety Review for Gas Turbines and SOFC, Washington D.C., USA, 2023.

- [4] Li, Q., Zhou, C. and He, Y., A Review of Hydrogen Energy in the Renewable Energy Supply Chain, Sustainability, Vol. 17, No. 5, 2310, 2025, <https://doi.org/10.3390/su17052310>.
- [5] Khan, F., Rathnayaka, S. and Ahmed, S., Methods and Models in Process Safety and Risk Management: Past, Present and Future, Process Safety and Environmental Protection, Vol. 98, pp 116–147, 2015, <https://doi.org/10.1016/j.psep.2015.07.005>.
- [6] Kim, D.-H., Lee, J.-H., Park, S.-Y. and Choi, J.-W., Quantitative Risk Assessment of a Mobile Hydrogen Refueling Station in Korea, International Journal of Hydrogen Energy, Vol. 47, No. 78, pp 33541–33549, 2022, <https://doi.org/10.1016/j.ijhydene.2022.07.194>.
- [7] Gye, H.-R., Kim, J.-H., Choi, S.-K. and Yoon, E.-S., Quantitative Risk Assessment of an Urban Hydrogen Refueling Station, International Journal of Hydrogen Energy, Vol. 44, No. 2, pp 1288–1298, 2019, <https://doi.org/10.1016/j.ijhydene.2018.11.035>.
- [8] Koromila, I., Papadopoulos, A. and Tsatsaronis, G., Safety of Hydrogen as a Marine Fuel: A Systematic Literature Review, Chemical Engineering Transactions, Vol. 116, pp 121–132, 2025, <https://doi.org/10.3303/CET25116022>.
- [9] Cardella, U., Decker, L. and Klein, H., Roadmap to Economically Viable Hydrogen Liquefaction, International Journal of Hydrogen Energy, Vol. 42, No. 19, pp 13329–13338, 2017, <https://doi.org/10.1016/j.ijhydene.2017.03.123>.
- [10] Mannan, M. R., Lees' Loss Prevention in the Process Industries, 4th ed., Elsevier, Oxford, UK, 2012.
- [11] Salzano, E., Basco, A., Crescitelli, S. and Russo, G., Hydrogen Risks and Safety Solutions, Chemical Engineering Transactions, Vol. 82, pp 19–24, 2020, <https://doi.org/10.3303/CET2082004>.
- [12] Clean Hydrogen Partnership, Hydrogen Valleys Annual Report, Brussels, Belgium, 2024.
- [13] International Energy Agency, Global Hydrogen Review 2022, Paris, France, 2022.
- [14] Kwon, D., Choi, S. K. and Yu, C., Improved Safety by Cross-Analyzing Quantitative Risk Assessment of Hydrogen Refueling Stations, International Journal of Hydrogen Energy, Vol. 47, No. 19, pp 10788–10798, 2022, <https://doi.org/10.1016/j.ijhydene.2021.12.211>.
- [15] Li, H., Zhang, K. and Lin, W., Integrating Safety Management Systems in Hydrogen Production Facilities, International Journal of Hydrogen Energy, Vol. 50, No. 7, pp 18531–18547, 2025, <https://doi.org/10.1016/j.ijhydene.2025.01.102>.
- [16] Genova, B., Silvestrini, M. and Leon Trujillo, F. J., Evaluation of the Blast-Wave Overpressure and Fragments Initial Velocity for a BLEVE Event, Journal of Loss Prevention in the Process Industries, Vol. 21, No. 1, pp 110–117, 2008, <https://doi.org/10.1016/j.jlp.2007.05.006>.
- [17] Cirrone, D., Makarov, D. and Molkov, V., Rethinking BLEVE Explosion After Liquid Hydrogen Storage Tank Rupture in a Fire, International Journal of Hydrogen Energy, Vol. 48, No. 56, pp 21014–21025, 2023, <https://doi.org/10.1016/j.ijhydene.2022.09.114>.
- [18] Cirrone, D., Makarov, D. and Molkov, V., The Multi-Peaks Structure of the Blast Wave Generated by a Liquid Hydrogen Storage Tank BLEVE, Chemical Engineering Transactions, Vol. 116, pp 421–428, 2025, <https://doi.org/10.3303/CET25116042>.
- [19] Shi, J., Chen, D., Zhao, Y. and Wang, L., Methodological Improvements in Hydrogen Risk Analysis, Journal of Cleaner Production, Vol. 257, 120545, 2020, <https://doi.org/10.1016/j.jclepro.2020.120545>.
- [20] Kim, J. H., Choi, S. K. and Yoon, E. S., Risk Assessment and Safety Analysis of Hydrogen Energy Systems: A Review of Methodologies and Applications, International Journal of Hydrogen Energy, Vol. 38, No. 34, pp 14838–14850, 2013, <https://doi.org/10.1016/j.ijhydene.2013.09.045>.
- [21] Calabrese, M., Rossi, L. and Gentile, A., Hydrogen Safety Challenges: A Comprehensive Review, Energies, Vol. 17, No. 6, 1350, 2024, <https://doi.org/10.3390/en17061350>.

- [22] Molkov, V., Fundamentals of Hydrogen Safety Engineering I, Bookboon, London, UK, 2012.
- [23] European Commission, REPowerEU Progress Report, Brussels, Belgium, 2024.
- [24] European Hydrogen Backbone Initiative, EHB Map and Report, Brussels, Belgium, 2024.
- [25] Kodoth, M., Nair, A., Raghavan, V. and Khan, F., Leak Frequency Analysis for Hydrogen-Based Technology Using Bayesian and Frequentist Methods, Process Safety and Environmental Protection, Vol. 136, pp 148–156, 2020, <https://doi.org/10.1016/j.psep.2020.01.025>.
- [26] Zarei, E., Khan, F. and Yazdi, M., A Dynamic Risk Model for Hydrogen Infrastructure, International Journal of Hydrogen Energy, Vol. 46, No. 5, pp 4626–4643, 2021, <https://doi.org/10.1016/j.ijhydene.2020.10.191>.
- [27] Enel Green Power, NextHy Initiative Summary, Rome, Italy, 2024, <https://www.enelgreenpower.com/>, [Accessed: 15-May-2026].
- [28] SNAM, Strategic Plan 2025–2029 Hydrogen Backbone, Milan, Italy, 2025, <https://www.snam.it/en/>, [Accessed: 15-May-2026].
- [29] Rahman, S. and Chen, Y., Hydrogen Safety in Energy Infrastructure: A Review, Energies, Vol. 18, No. 20, 5470, 2025, <https://doi.org/10.3390/en18205470>.
- [30] Subedi, A., Khan, F., Amyotte, P. and Abbassi, R., Reframing Safety Barriers as Socio-Technical Systems, Safety Science, Vol. 172, 106095, 2025, <https://doi.org/10.1016/j.ssci.2025.106095>.
- [31] Ocko, I. B. and Hamburg, S. P., Effect of Hydrogen Leakage on Climate Impacts, Communications Earth & Environment, Vol. 6, 141, 2025, <https://doi.org/10.1038/s43247-025-02141-3>.
- [32] Zhang, Y., Wang, J. and Liu, F., Optimisation of Hydrogen Supply Chain Under Uncertainties, Energy, Vol. 289, 130456, 2025, <https://doi.org/10.1016/j.energy.2024.130456>.
- [33] Mukoni, E. and Garner, K. S., Multi-Objective Optimisation for Hydrogen Systems, Energies, Vol. 15, No. 19, 7079, 2022, <https://doi.org/10.3390/en15197079>.
- [34] Crowl, D. A. and Louvar, J. F., Chemical Process Safety: Fundamentals with Applications, 3rd ed., Pearson Education, Boston, USA, 2011.
- [35] Molkov, V. and Kashkarov, S., Blast Wave from a High-Pressure Gas Tank Rupture in a Fire, International Journal of Hydrogen Energy, Vol. 40, No. 38, pp 12581–12603, 2015, <https://doi.org/10.1016/j.ijhydene.2015.07.075>.
- [36] Pehr, K., Aspects of Safety of LH2 Tank Systems, International Journal of Hydrogen Energy, Vol. 21, No. 5, pp 387–395, 1996, [https://doi.org/10.1016/0360-3199\(95\)00113-1](https://doi.org/10.1016/0360-3199(95)00113-1).
- [37] San Marchi, C. and Somerday, B. P., Technical Reference for Hydrogen Compatibility of Materials, Sandia National Laboratories, Albuquerque, USA, 2012.
- [38] International Electrotechnical Commission, IEC 61508 Functional Safety Standard, Geneva, Switzerland, 2010.
- [39] International Organization for Standardization (ISO), ISO/TR 15916 Hydrogen Safety Considerations, Geneva, Switzerland, 2015.
- [40] Edalati, K., Arita, M. and Horita, Z., Impact of Severe Plastic Deformation on Hydrogen Storage Kinetics in Magnesium and Its Alloys, International Journal of Hydrogen Energy, Vol. 48, No. 4, pp 1156–1170, 2023, <https://doi.org/10.1016/j.ijhydene.2023.10.043>.
- [41] Sun, B., Li, Y., Zhang, T. and Chen, H., Safety and Sustainability of Natural Hydrogen Wells, Nature Communications, Vol. 16, No. 1, 369, 2025, <https://doi.org/10.1038/s41467-024-55773-y>.
- [42] Ustolin, F., Paltrinieri, N. and Berto, F., Mechanical Energy in Rupture of Hydrogen Tanks, Chemical Engineering Transactions, Vol. 91, pp 421–426, 2022, <https://doi.org/10.3303/CET2291071>.

- [43] Ustolin, F., Paltrinieri, N. and Berto, F., Loss of Integrity of Hydrogen Technologies, *International Journal of Hydrogen Energy*, Vol. 47, No. 32, pp 14555–14573, 2022, <https://doi.org/10.1016/j.ijhydene.2022.02.058>.
- [44] DNV, *Hydrogen Forecast to 2050: Energy Transition Outlook 2021*, Oslo, Norway, 2021.
- [45] European Commission, *European Integrated Hydrogen Project (EIHP) and IPCEI Hy2Infra: Roadmap for Hydrogen Infrastructure and Safety Integration*, Brussels, Belgium, 2024.
- [46] ENI and SNAM, *Ravenna CCS Project Overview*, Rome, Italy, 2024, <https://www.eni.com/> and <https://www.snam.it/en/>, [Accessed: 15-May-2026].
- [47] Kim, C., Lee, Y. and Kim, K., Comparative Risk Assessment of a Hydrogen Refueling Station Using Gaseous Hydrogen and Formic Acid, *Energies*, Vol. 16, No. 6, 2613, 2023, <https://doi.org/10.3390/en16062613>.
- [48] Lin, Y., Zhang, W. and Lu, C., Resilience-Assuring Hydrogen-Powered Microgrids, *Applied Energy*, Vol. 346, 121402, 2023, <https://doi.org/10.1016/j.apenergy.2023.121402>.
- [49] Suzuki, T., Nakamura, Y., Sato, H. and Ito, K., Quantitative Risk Assessment Using a Japanese Hydrogen Refueling Station Model, *International Journal of Hydrogen Energy*, Vol. 46, No. 11, pp 8329–8343, 2021, <https://doi.org/10.1016/j.ijhydene.2020.12.035>.
- [50] Wang, H., Liu, X., Zhao, J. and Chen, Y., Optimisation of Renewable Hydrogen Systems, *Energies*, Vol. 17, No. 10, 2384, 2024, <https://doi.org/10.3390/en17102384>.
- [51] Wang, X. and Gao, W., Hydrogen Leakage Risk Assessment, *International Journal of Hydrogen Energy*, Vol. 48, No. 91, pp 35795–35808, 2023, <https://doi.org/10.1016/j.ijhydene.2023.05.340>.
- [52] Yoo, B.-H., Kim, J.-S., Lee, H.-K. and Park, Y.-J., Comparative Risk Assessment of Hydrogen Refueling Stations, *International Journal of Hydrogen Energy*, Vol. 46, No. 71, pp 35511–35524, 2021, <https://doi.org/10.1016/j.ijhydene.2021.08.073>.
- [53] Mohammadi, M. and Zhang, R., High-Entropy Hydrides for Hydrogen Storage, *Journal of Alloys and Compounds*, Vol. 951, 170109, 2023, <https://doi.org/10.1016/j.jallcom.2023.170109>.
- [54] Cirrone, D., Makarov, D. and Molkov, V., The Multi-Peaks Structure of the Blast Wave Generated by a Liquid Hydrogen Storage Tank BLEVE, *International Journal of Hydrogen Energy*, Vol. 133, pp 416–430, 2025, <https://doi.org/10.1016/j.ijhydene.2025.04.222>.
- [55] Yuan, W., Li, X., Zhao, H. and Chen, J., Numerical Investigation of Leakage and Explosion Scenarios, *International Journal of Hydrogen Energy*, Vol. 47, pp 18786–18798, 2022, <https://doi.org/10.1016/j.ijhydene.2022.04.060>.

APPENDIX A

Table A1: Context–intervention–mechanism–outcome (CIMO) classification of representative studies.

Ref.	Context	Intervention	Mechanism	Outcome
[4]	Hydrogen supply chain	Literature review	Comparative synthesis	Integration challenges
[6]	Mobile hydrogen	Quantitative risk assessment	Frequency–consequence analysis	Individual risk metrics

Ref.	Context	Intervention	Mechanism	Outcome
	refuelling station (Korea)			
[7]	Urban hydrogen refuelling station	Quantitative risk assessment	Scenario-based modelling	Risk acceptability
[8]	Marine hydrogen fuel systems	Literature review	Safety comparison	Hazard identification
[9]	Hydrogen liquefaction systems	Techno-safety assessment	Process modelling	Liquefaction safety pathways
[14]	Hydrogen refuelling stations	Comparative risk assessment	Cross-station comparison	Safety improvement indicators
[15]	Hydrogen production facilities	Safety management integration	Organisational- process linkage	Safety performance
[17]	Liquid hydrogen storage tank	Consequence modelling	BLEVE simulation	Blast effects
[18]	Liquid hydrogen BLEVE	Blast-wave modelling	Overpressure analysis	Multi-peak blast structure
[19]	Hydrogen safety systems	Methodological review	Risk-method comparison	Analytical limitations
[20]	Hydrogen energy systems	Literature review	Methodological synthesis	Risk assessment overview
[21]	Hydrogen infrastructure	Safety review	Hazard synthesis	Safety challenges
[25]	Hydrogen technologies	Bayesian assessment	Probabilistic updating	Leak-frequency estimation
[26]	Hydrogen infrastructure	Dynamic modelling	Dynamic probabilistic update	Risk evolution
[30]	Hydrogen safety barriers	Socio-technical analysis	Barrier-function assessment	Barrier effectiveness
[32]	Hydrogen supply chain	Optimisation under uncertainty	Scenario optimisation	Decision support
[35]	High-pressure hydrogen tanks	Consequence modelling	Blast-wave simulation	Overpressure estimation
[42]	Hydrogen tank rupture	Mechanical energy analysis	Rupture modelling	Energy release estimation
[43]	Hydrogen technologies	Integrity analysis	Failure modelling	Loss-of- integrity assessment
[51]	Hydrogen leakage systems	Leakage assessment	Sensor-supported analysis	Leakage indicators

Note: representative studies included in the PRISMA corpus and directly relevant to hydrogen safety and risk assessment were classified using the CIMO framework. Foundational and contextual references used exclusively for background purposes were not systematically coded.

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