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Risk Analysis of the Hydrogen Supply Chain

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This study addresses the issue of risk analysis within the hydrogen supply chain, proposing an integrated methodological approach for the assessment and mitigation of hazards throughout the entire operational cycle. The goal is to develop a methodological framework capable of representing, analyzing and optimizing the safety processes associated with the hydrogen value chain, with particular emphasis on the use of physical and digital safety barriers supported by advanced sensing technologies. The methodology is applied to two representative case studies: a green hydrogen supply and a BLEVE-type event involving a cryogenic storage tank. The results suggest that the integrated approach may improve significantly the ability to identify hazardous conditions at an early stage and to reduce response times. The application of the methodology to selected case studies has shown that safety barriers can be calibrated according to operational conditions and the criticality of individual processes.

Keywords: Hydrogen supply chain; Quantitative Risk Analysis (QRA); Safety barriers; Process safety

1. Introduction

The transition towards a low-carbon energy system constitutes one of the defining challenges of the twentieth century. Within this broader transformation, hydrogen is increasingly recognized as a strategic energy vector with the potential to support the decarbonization of industrial sectors—most notably steel production, chemical manufacturing, and heavy-duty transport. Its versatility, together with its capacity to integrate with renewable energy sources, positions hydrogen as a pivotal enabler of a more sustainable industrial landscape.

Despite its strategic relevance, the hydrogen supply chain (HSC) presents a number of inherent safety concerns and derive from the specific physicochemical properties of hydrogen and from the operational conditions under which it is produced, stored, transported, and distributed. High flammability, a wide explosion range, and the frequent use of cryogenic temperatures require robust and integrated risk-analysis approaches capable of accounting for hazards across the entire value chain.

This paper aims to develop a structured methodology for risk analysis within the hydrogen supply chain, combining qualitative and quantitative techniques and supporting the design and optimization of physical and digital safety barriers. The methodology integrates traditional tools such as HAZOP, FTA, and bow-tie analysis with modern IoT sensors, real-time monitoring platforms, and multi-objective optimization algorithms.

Finally, the methodology is applied to two representative case studies: a green hydrogen supply chain and a BLEVE-type event involving a cryogenic LH_2 tank, demonstrating the effectiveness of the proposed integrated framework in improving safety and reducing residual risk.

2. Related Works

In recent years, scientific literature has shown growing interest in risk management along the hydrogen value chain, with particular emphasis on production, storage, transport and distribution processes. The complexity of these systems, combined with the physical properties of hydrogen (wide flammability range and low ignition energy), requires the adoption of integrated methodological approaches for the prevention and mitigation of accidental events. Several authors have examined Quantitative Risk Analysis (QRA) models applied to hydrogen-related processes, focusing on the assessment of the probability of loss of containment and the modelling of consequences Russo and Fabiano (2023); Zhang et al. (2023) . These studies emphasize the importance of considering operational variables such as pressure, temperature, and plant configuration in estimating damage thresholds.

A complementary line of research concerns the study of domino effects and Boiling Liquid Expanding Vapour Explosion (BLEVE) events, which are typical of cryogenic conditions and liquid storage systems. Computational Fluid Dynamics (CFD) analyses, integrated with probabilistic models such as QRA, make it possible to estimate the propagation of thermal radiation and overpressure effects, providing useful insights for the design of protective barriers Abbasi and Abbasi (2022). At the same time, recent literature has placed increasing emphasis on the design of multilayer safety barriers, both physical and organisational, capable of interrupting the cause–effect chain of accidental events. Catena et al. (2024) propose a combined approach based on bow-tie diagrams and the assessment of barrier effectiveness, demonstrating how the integration of preventive and mitigative measures can significantly reduce residual risk.

A further development is represented by the digitalisation of industrial safety. Technologies such as the Industrial Internet of Things (IIoT) and advanced sensor systems enable continuous monitoring of critical parameters (pressure, temperature, flow rate), supporting the transition from a reactive to a predictive safety logic. Recent studies Li et al. (2025); Kim and Lee (2024) have shown that the use of sensors integrated with machine-learning algorithms can reduce response times in critical situations by up to 40% and enhance early diagnosis of operational anomalies.

Table 1 summarizes a selection of representative contributions from the scientific literature on safety throughout the hydrogen value chain.

An emerging aspect is the integration of risk analysis with digital technologies. The concept of the digital twin applied to safety is gaining increasing prominence: through real-time simulation and processing of data collected by sensors, it becomes possible to evaluate dynamic risk scenarios and update mitigation strategies accordingly. The model proposed in this paper aligns with this perspective, offering a unified approach that combines risk assessment, barrier design and intelligent monitoring to optimize the resilience of the hydrogen supply chain.

Author	Year	Approach	Main result
Fabiano M. et al.	2023	Integrated QRA	Identification of critical phases in H_2 transport
Abbasi T., Abbasi S.	2022	Systemic analysis	Need for harmonised safety standards
Catena S. et al.	2024	Bow-tie + barriers	Effectiveness of multilevel mitigation
Zhang et al.	2021	CFD + QRA	Dynamic estimation of cryogenic dispersion
Russo A. et al.	2023	Risk-based design	Cost–safety optimisation in the supply chain

3. Methodological Model for Risk Analysis of the Hydrogen Supply Chain

The proposed methodology is based on an integrated approach that combines qualitative and quantitative tools of risk analysis for the evaluation of safety along the hydrogen value chain. The main objective is to support the design and optimisation of safety barriers, both physical and digital, capable of mitigating the risks associated with each phase of the operational cycle: production, storage, transport and distribution.

3.1. *General Structure of the Model*

The model is structured into four main phases (Figure 1 conceptually):

(1) **Identification of the critical stages of the supply chain.**
Each segment of the supply chain (electrolysis, compression, liquefaction, transport, distribution and end-use) is analysed to identify potential hazardous events (hazard identification). This analysis is based on established techniques such as Hazard and Operability Study (HAZOP) and What-if Analysis, integrated with data from the scientific literature and accident databases (e.g. HIAD, eMARS).

(2) **Risk assessment.**
For each identified event, both the frequency of occurrence and the severity of the consequences are estimated. The analysis combines an initial qualitative approach (risk matrix) with simplified quantitative tools such as Fault Tree Analysis (FTA) for estimating failure probability and Event Tree Analysis (ETA) for modelling effect propagation. In this phase, risk indicators (Risk Index) and acceptability thresholds are determined.

(3) **Design of safety barriers.**
Safety barriers are classified according to the bow-tie methodology, distinguishing between:

- *Preventive barriers*, intended to reduce the likelihood of release or failure (safety valves, isolation systems, process controls);
- *Mitigative barriers*, aimed at limiting the consequences of an event (fire-fighting systems, ventilation, hydrogen detectors, emergency plans).

The model explicitly considers the integration of intelligent sensor systems (catalytic, optical and fibre-optic sensors) with digital platforms capable of processing real-time data to enable the automatic activation of mitigative barriers.

Fig. 1. Proposed methodological model for supply chain risk management.

(4) **Multi-objective optimization.**
The final phase involves the use of multi-objective optimization techniques to identify the configuration of barriers that maximizes overall safety while simultaneously minimizing costs and response times.

The objective function can be expressed in terms of residual risk $R(x)$, cost $C(x)$ and activation time $T(x)$, for a given barrier configuration x:

$$\min_{x}\{R(x),\, C(x),\, T(x)\}. \qquad (1)$$

Different solutions along the Pareto front represent alternative trade-offs between safety performance and economic feasibility. For clarity and reproducibility, Phase 1 outputs a structured set of initiating events based on HAZOP and accident databases; Phase 2 quantifies frequency and consequence through FTA/ETA and predefined acceptability thresholds; Phase 3 defines preventive and mitigative barrier configurations, including digital sensing layers; and Phase 4 selects Pareto-optimal solutions balancing residual risk, cost and activation time. In the analysed cases, detection-time reduction is mainly driven by the digital monitoring layer (Phase 3), whereas residual-risk reduction is primarily associated with barrier configuration optimisation (Phase 4).

3.2. *Support Tools and Technologies*

The model integrates continuous monitoring tools based on Internet of Things (IoT) technologies, Supervisory Control and Data Acquisition (SCADA) systems and distributed sensor networks capable of collecting critical parameters (pressure, temperature, H_2 concentration). The data are processed by predictive algorithms that anticipate hazardous conditions and suggest automatic or assisted corrective actions.

The adoption of such systems enables the transition from a reactive safety logic to a predictive one, in which risk analysis is no longer static but dynamic and adaptive, depending on real operating conditions.

3.3. *Application and Validation*

The model is applied to two representative case studies:

- a green hydrogen supply chain serving energy-intensive industrial sectors;
- a BLEVE event involving a cryogenic LH_2 tank, analysed in terms of barrier response and shock-wave mitigation.

The two case studies were selected to represent complementary and recurrent configurations within hydrogen infrastructures. The first case reflects a distributed green hydrogen supply chain involving production, compression, transport and refuelling stages, typical of emerging industrial applications. The second case represents a cryogenic liquid hydrogen storage scenario, where low-frequency high-consequence events such as BLEVE constitute a major safety concern. Together, they cover both continuous operational risk and acute accidental scenarios. These applications make it possible to validate the methodology, highlighting the effectiveness of the designed barriers and the model's ability to support engineering decisions based on quantitative data.

4. Case Study 1: Green Hydrogen Supply Chain

4.1. *System Description*

The modelled system comprises the stages of production via alkaline electrolysis, compression to 700 bar, intermediate storage, road transport using high-pressure trailers and refuelling at urban stations. Three categories of logistical stakeholders were considered: the producer, the transporter and the distributor.

The main risks identified through the hazard identification (HAZID) analysis are:

- loss of containment at flanged connections;
- overpressure during the compression phase;
- failure of the safety valve;
- mechanical impact during transport.

4.2. *Quantitative Risk Analysis*

The Quantitative Risk Analysis (QRA) was carried out using the reference parameters reported in Table 2. For each event, an annual probability P and a consequence measure C (expressed in terms of equivalent energy in MJ) were associated. The risk indicator R is obtained as the product $R = P \times C$.

Table 2. Summary of events and risk indicators for the transport system.

Event	P (yr^{-1})	C [MJ]	R
Flange rel.	2.3×10^{-3}	12	0.0276
Overpressure	1.1×10^{-3}	25	0.0275
Valve fail.	8.0×10^{-4}	30	0.0240
Mech. impact	4.0×10^{-4}	50	0.0200

The resulting average total risk for the transport system is therefore:

$$R_{\text{tot}} = \sum_i P_i C_i \approx 9.9 \times 10^{-2}. \qquad (2)$$

The most critical points are the flanged connections and the compression phase, which account for approximately 45% of the potential releases. The bow-tie analysis showed that the predominant causes are associated with thermal stress and mechanical vibrations affecting the fittings.

4.3. *Implementation of Barriers and Sensor Systems*

A combination of preventive and mitigative barriers was introduced to enhance the safety of the system. These included rapid-response thermal sensors (Resistance Temperature Detectors, RTDs, with a sampling time of 0.5 s), as well as flow and pressure sensors integrated into a wider IoT-based monitoring network. In addition, automatic isolation valves and forced-ventilation units were installed at loading and unloading areas to reduce the likelihood and potential severity of accidental releases.

The data collected by the sensor network were processed through a predictive anomaly-detection algorithm based on logistic regression. This enabled the system to identify abnormal operating conditions significantly earlier than before. As a result, the average detection time was reduced from about 30 seconds (30 s) to approximately 7 s, which in turn led to a reduction in the overall risk level of around 32%.

4.4. *Multi-objective Optimization*

The multi-objective optimization stage was conducted using the Non-dominated Sorting Genetic Algorithm II (NSGA-II), implemented with a population of 100 individuals and 200 generations. This configuration ensured adequate exploration of the design space while maintaining computational efficiency, thereby enabling a systematic comparison of alternative safety-barrier architectures.

The optimisation results are summarised by the Pareto front shown conceptually in Figure 2, which captures the trade-off between investment costs and the level of residual risk. The curve clearly reflects the intrinsic tension between these two objectives: configurations that incorporate more advanced sensing solutions or additional mitigative barriers generally achieve a lower residual risk, yet they do so at the expense of higher implementation and maintenance costs. Conversely, leaner configurations reduce expenditure but tend to offer less robust protection, leading to higher residual risk values.

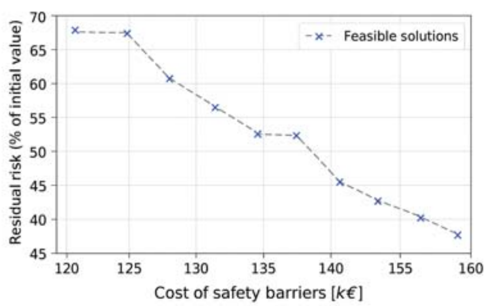

Fig. 2. Feasible solutions along the Pareto front between residual risk and cost of safety barriers.

A closer inspection of the Pareto-optimal set reveals that the most promising solutions cluster within a relatively narrow cost interval—approximately 120–160 k euro. Within this range, several configurations succeed in reducing residual risk to below 70% of the baseline scenario. This outcome demonstrates that meaningful improvements in safety performance can be achieved without requiring disproportionate financial investment. From an engineering-decision perspective, these configurations therefore represent a balanced and realistic compromise between technical effectiveness and economic feasibility.

5. Case Study 2: BLEVE Event Involving a Liquid Hydrogen Tank

5.1. *Description and Physical Model*

The second case study examines a BLEVE event occurring in a liquid hydrogen storage tank operated at 20 K and 5 bar. The simulation framework draws upon experimental data from the literature and employs simplified models describing internal energy release and overpressure generation. In particular, the pressure rise is estimated using a thermodynamic balance that links the energy input, the vapour expansion and the failure conditions of the tank wall.

The BLEVE dynamics were simulated under three distinct scenarios:

- S1 – No barriers: baseline configuration with no thermal or mechanical protections;
- S2 – Passive thermal barriers: introduction of reflective aluminium shielding to delay heat transfer and slow pressurisation;
- S3 – Combined passive and active barriers: passive shielding complemented by controlled relief valves designed to prevent critical overpressure conditions.

This structure allows a systematic comparison of how different protection strategies influence the pressure curve, failure timing and explosion severity.

The simulation results for the three scenarios are summarised in Table 3. The indicators considered are peak pressure, flame temperature and lethal damage radius.

The results indicate a clear and progressive attenuation of the BLEVE severity as additional protective measures are introduced. Moving from the unprotected configuration (S1) to the combined passive–active system (S3), the peak pressure is reduced by approximately 43%, while the flame temperature decreases by around 350 °C. A similar trend is observed for the lethal damage radius, which contracts from 180 m to 110 m, corresponding to a reduction of roughly 40%.

Scenario	Peak pressure [bar]	Flame temp. [°C]	Lethal radius [m]
S1	3.2	2100	180
S2	2.4	1900	140
S3	1.8	1750	110

These findings indicate the potential effectiveness of combining passive thermal barriers with controlled relief valves. In particular, the integration of cryogenic sensors and actively managed discharge valves enables earlier system depressurisation—approximately 12 s before the structural collapse threshold is reached. This anticipatory action plays a key role in limiting the intensity of the explosion and reducing the spatial extent of hazardous effects.

6. Comparison Between the Two Case Studies

The two case studies illustrate the versatility of the proposed methodology, which appears applicable to both continuous operational systems and acute accidental scenarios within the analysed configurations. Table 4 summarises the main results.

Taken together, these results provide a comparative overview of how the proposed methodology performs under different operational conditions.

Indicator	Case 1: Green H_2 supply chain	Case 2: BLEVE on LH_2
Total risk reduction	$\approx 32\%$	$\approx 43\%$
Average fault detection time	7 s (from 30 s)	12 s anticipation vs. collapse
Type of sensors	thermal, flow, pressure	cryogenic, pressure
Type of barriers	physical + digital	thermal + relief valves
Reduction of damage radius	–	$\approx 40\%$
Optimisation approach	NSGA-II	QRA + physical simulation
Final result	Residual risk $< 70\%$ of baseline	Max pressure 1.8 bar

7. Discussion of Results

The results suggest that the digitalisation of monitoring systems and the integrated design of safety barriers can enhance the overall resilience of hydrogen infrastructures within the analysed scenarios. In both applications, the combined approach—integrating quantitative risk analysis, safety-barrier design and real-time monitoring—was associated with a reduction in residual risk and shorter reaction times under abnormal operating conditions.

In Case 1 (green hydrogen supply chain), the average probability of critical failure decreases significantly, corresponding to a reduction in total risk of approximately 32%, while the mean detection time is reduced from about 30 s to 7 s. The overall effectiveness of the preventive barriers increases from an initial value (about 0.72) to around 0.86 on a 0–1 scale, which represents an improvement in reliability of roughly 19%.

In Case 2 (BLEVE involving an LH_2 tank), the integration of passive barriers and controlled valves reduces the maximum peak pressure from 3.2 bar to 1.8 bar, corresponding to a mitigation factor of about 0.44. Flame temperature decreases by approximately 350 °C and the lethal damage radius is reduced by about 40%, indicating a substantial enhancement of the physical safety of the installation.

From an economic perspective, the NSGA-II optimisation algorithm identifies Pareto-optimal configurations that reduce residual risk by around 35% while achieving an average cost reduction of about 12% compared with conventional safety-design solutions. The mean reliability value of the optimised system reaches approximately 0.88, compared with 0.73 for the baseline configuration.

7.1. *Practical Implications*

The application of the methodology shows that the combination of physical and digital barriers enables simultaneous improvements in both safety and economic sustainability. IoT-based sensing, integrated with predictive algorithms, emerges as a key element in the transition from reactive risk management to a proactive approach grounded in the principle of early detection.

In particular:

- the reduction in response time (to below 10 s) makes it possible to limit energy release by more than 25% compared with a non-monitored system;
- the increase in barrier reliability significantly reduces the probability of accidents with severe consequences;
- the average benefit–cost ratio (risk reduction vs. investment) reaches values of the order of 2.8, confirming the technical and economic convenience of the proposed approach.

Although derived from simulations, these results indicate that the methodology may serve as an operational support tool for infrastructure operators, regulatory authorities and industrial stakeholders in the design of safe and resilient hydrogen systems.

Furthermore, the digitalisation of monitoring establishes the foundations for the future implementation of a safety-oriented digital twin, which could be integrated into industrial supervisory systems such as SCADA platforms or IoT hubs. Overall, the integrated methodology presented in this work appears capable of delivering measurable improvements in the safety and performance of hydrogen systems within the analysed configurations. Furthermore, risk was reduced by approximately 30–40% within the analysed configurations, while the reliability of safety barriers can be increased to values close to 0.9, indicating a more robust and dependable protection architecture. At the same time, the optimisation process allows safety costs to be streamlined, with average savings of 10–15%, demonstrating that enhanced safety does not necessarily require proportionally higher investment. A further benefit concerns the system's dynamic response: the ability to detect and react to critical events more rapidly—by more than 20 s in some scenarios—significantly limits the escalation potential of hazardous situations. This improvement stems directly from the integration of digital monitoring, predictive analytics and physical protection measures within a unified framework.

Taken together, these outcomes show that the methodology is not only effective for the hydrogen supply chain, but also sufficiently flexible to be replicated in other high-risk energy contexts. Its structure makes it applicable to the safety design of infrastructures for biomethane, green ammonia and other emerging technologies that will play a central role in the ongoing energy transition.

7.2. *Limitations*

The present study is based on two case studies and relies partly on literature-based and estimated parameters. The BLEVE modelling adopts simplified thermodynamic formulations rather than full CFD simulations, and no formal uncertainty or sensitivity analysis has been conducted. Consequently, the numerical results should be interpreted as indicative trends within the analysed configurations rather than universally generalisable outcomes. Further validation on industrial datasets and extended stochastic modelling would strengthen the robustness of the quantitative findings.

8. Conclusions

The proposed study has addressed the issue of risk analysis within the hydrogen supply chain, proposing an integrated methodological approach for the assessment and mitigation of hazards throughout the entire operational cycle. The objective was to establish a methodological framework capable of representing, analyzing and optimizing the safety processes associated with the hydrogen value chain, with particular emphasis on the use of physical and digital safety barriers supported by advanced sensing technologies.

The results of the proposed model indicate that the integration of traditional analysis methods (HAZOP, FTA, bow-tie) with digital tools based on sensors and monitoring platforms can significantly enhance the ability to identify hazardous conditions at an early stage and to reduce response times. This combined approach contributes to lowering residual risk and increasing the overall resilience of the system, promoting a proactive rather than reactive approach to safety across the supply chain.

The application of the model to the selected case studies (a green hydrogen supply chain and a BLEVE-type event involving a cryogenic storage tank) suggests that safety barriers can be calibrated according to operational conditions and the criticality of individual processes. The integration of sensor technologies also enables the transformation of raw data into actionable information for decision-making, paving the way for dynamic and adaptive risk management.

From both a scientific and practical perspective, this research provides a basis for future developments aimed at:

- expanding the model to include environmental and socio-economic parameters, allowing the assessment of the broader impacts of mitigation strategies;
- implementing machine-learning algorithms for predictive fault diagnosis and the automatic optimisation of safety barriers;
- extending the application of the model to urban-scale and infrastructure-scale distribution networks, within a safety-by-design and

resilience-planning perspective.

References

Abbasi, T. and S. Abbasi (2022). The hydrogen energy economy: A risk analysis perspective. *Renewable and Sustainable Energy Reviews 165*, 112551.

Catena, S., L. Rossi, and M. Fabiano (2024). Safety barriers design in hydrogen systems: A multilevel approach. *Journal of Loss Prevention in the Process Industries 89*, 105301.

Kim, J. and S. Lee (2024). Application of iot and machine learning for early hazard detection in hydrogen facilities. *Safety Science 170*, 106487.

Li, Q., C. Zhou, and Y. He (2025). A review of hydrogen energy in the renewable energy supply chain. *Sustainability 17*(5), 2310.

Russo, A. and M. Fabiano (2023). Quantitative risk assessment of hydrogen supply chains. *Process Safety and Environmental Protection 174*, 383–396.

Zhang, H., J. Li, and Y. Wang (2023). Cfd and qra coupling for hydrogen leak and dispersion scenarios. *International Journal of Hydrogen Energy 48*(12), 4712–4725.