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Storm-induced Natech vulnerability of safety barriers in large-scale liquid hydrogen storage systems

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The ongoing transition toward large-scale liquid hydrogen (LH_2) storage systems, both onshore and offshore, introduces new safety challenges associated with cryogenic operating conditions and increased exposure to natural hazard-triggered technological (Natech) accidents. In parallel, the adoption of novel insulation concepts, essential to improve thermal efficiency and reduce boil-off losses, brings new uncertainties regarding the behaviour and long-term reliability of safety barriers. Within this context, the present work investigates the interaction between storm-related natural hazards and selected safety barriers installed on large-scale stationary LH_2 storage tanks. The analysis focuses on representative preventive, mitigative and detection barriers adopting a structured What-If-based approach to identify how physically plausible storm-induced damage mechanisms may compromise their functional performance. Particular attention is devoted to storm-related Natech events, including strong winds, heavy precipitation and flooding, storm surge and lightning, with the aim of highlighting specific barrier vulnerabilities and potential escalation pathways. The results provide qualitative insights into the resilience (in terms of functional robustness) of safety barriers under storm conditions and offer elements that may inform future resilience-oriented safety assessments and the development of guidelines for large-scale LH_2 storage systems.

Keywords: Liquid hydrogen, Storage tank, Safety barrier, Natech risk, What-If-based approach.

1. Introduction

The deployment of hydrogen as an energy carrier is expected to play a key role in the decarbonisation of several industrial sectors. In this context, liquid hydrogen (LH_2) storage systems are receiving increasing attention, as their anticipated scale-up introduces new technical and safety challenges. These issues are currently being addressed within the NICOLHy project (NICOLHy Project Consortium (2024)), which aims to develop and assess large-scale LH_2 storage solutions based on novel insulation technologies and innovative tank configurations.

In parallel, the exposure of industrial installations to natural hazard-triggered technological (Natech) accidents has gained increasing attention. Storm-related natural events have been identified as major contributors to Natech accidents affecting storage equipment: historical evidence from accident databases indicates that lightning is one of the most frequent causes of storm-induced Natech accidents across industrial sectors (European Commission and Joint Research Centre (2018)). Although hydrogen-related Natech events remain relatively limited in number, documented cases demonstrate that natural hazards can directly impact hydrogen installations. In particular, two hydrogen-related accidents triggered by natural events were initiated by lightning strikes, both resulting in the ignition of hydrogen intentionally released through venting systems (Campari et al. (2023)). In addition, strong winds have been reported to cause structural damage leading to pipework failure at a gaseous hydrogen refuelling station (Tzioutzios et al. (2025)).

Beyond documented accident statistics, the renewed interest in hydrogen technologies is revealing additional safety-relevant interactions that may become significant under storm-related conditions. For example, experiments have shown that the release of liquid hydrogen onto or into water – particularly at large scale – can result in a self-ignition phenomena (van Wingerden et al. (2022)). While such effects have not yet been explicitly linked to storm-induced scenarios, they indicate that environmental conditions involving water, such as flooding or heavy precipitation, may introduce additional pathways for risk escalation in large-scale LH_2 storage installation.

To address this gap, the present work investigates the vulnerability of selected safety barriers installed on large-scale LH_2 stationary storage tanks equipped with novel insulation systems when exposed to storm-related hazards. The analysis adopts a structured What-If-based approach to identify physically plausible interactions between storm-induced failure modes and safety barriers, with the aim of providing insights that can inform future safety assessments and guideline development for large-scale hydrogen storage systems.

2. Methodology

The methodological approach adopted in this work follows a structured, multi-step framework inspired by previous Natech investigations in the process industry (Schiaroli et al. (2024); Ricci et al. (2023)), here adopted to capture the specific interactions between relevant storm-induced failure mechanisms and the cryogenic hydrogen storage system.

As a first step, a systematic screening of relevant damage mechanisms was carried out based on consolidated Natech literature and official reports, as summarized in Table 1. Notably, these damage modes are specific to large storage tanks designed to hold hazardous materials which is the type of equipment with the highest frequency of releases due to storms (European Commission and Joint Research Centre (2018)) making them particularly relevant to the case study. For storm scenarios, four categories were considered:

(i) Heavy precipitation and flash flooding
(ii) Storm surge
(iii) Lightning
(iv) Strong wind

Table 1.: Damage modes triggered by storms (adapted from European Commission and Joint Research Centre (2018)).

Damage mode	(i)	(ii)	(iii)	(iv)
Sinking of floating roof	x		x	
Damage to electrical equipment	x	x	x	
Power loss	x	x	x	x
Flotation	x	x		
Displacement	x	x		x
Vessel buckling	x	x		x
Impact with floating objects	x	x		
Ignition of flammables	x		x	x
Thermal puncturing of containment			x	
Roof damage	x		x	x
Impact with airborne objects				x
Falling objects				x

For each natural event, the associated damage modes were collected and used as the primary triggers potentially affecting equipment functionality.

A comprehensive list of safety barriers for LH_2 storage systems was initially compiled based on previous work, drawing on an extensive review of international standards and industrial guidelines for cryogenic hydrogen storage, as well as on the results of a prior activities conducted within the NICOLHy project (NICOLHy Project Consortium (2024)) (Table 2).

This resulted in a baseline set – following the hierarchy of safeguards (after Kletz (Bollinger (2010)) – comprising:

- Inherently safer design measures
- Passive engineered safeguards
- Active engineered safeguards
- Administrative and procedural controls

A preliminary screening was then performed to select only those barriers whose functioning may be directly impaired by one or more storm-related damage modes. Barriers acting solely as hazard mitigators but not vulnerable to storm-induced failure modes (e.g., safety distances) were excluded. Ultimately, both inherently safer design measures and administrative or procedural controls were not retained for the subsequent stages of the analysis.

A second thorough screening was then guided by a two-fold criteria:

(a) *Scale amplification*: the loss of barrier functionality may lead to disproportionately more severe consequences in large-scale LH_2 storage systems compared to state-of-the-art small-scale tanks.

(b) *Interaction with novel insulation*: the barrier contributes to or depends on the performance of the insulation system.

Only the barriers satisfying at least one of these criteria were retained for detailed analysis (Fig. 1).

For each selected safety barrier, a "What-if" analysis was performed to evaluate how storm damage modes can compromise the barrier's ability to prevent, detect or mitigate hazardous conditions (Center for Chemical Process Safety (2008); Mannan (2005)). This step identifies the consequence pathways that link the natural trigger to the degradation of the specific barrier's performance. This mapping is the basis for the "What-If" assessment and directly informs the definition of safety recommendations to prevent their degradation or malfunctioning.

The present analysis does not include the assesment of the likelihood of safety barrier failure once a storm-induced damage mode occurs: for the failure mechanisms considered, the loss of barrier functionality is assumed to be deterministic, conditional upon the occurrence of the damaging interaction.

For each selected safety barrier, a set of targeted What-If questions was formulated. Each question is addressed by identifying:

- the primary consequence affecting the safety barrier
- the resulting effect on the system
- the corresponding risk-control actions, expressed as design or operational recommendations

The insights derived from the What-If analysis then provide useful elements to inform and support the development of future guidelines.

3. Results and discussions

Following the screening procedure described in Section 2, a reduced subset of three safety barriers was selected for detailed analysis, namely among those whose functionality may be significantly compromised by storm-induced damage modes and whose relevance is amplified in the context of large-scale LH_2 stationary storage systems equipped with novel insulation concepts. The remaining safety barriers identified during the screening process were not considered at this stage and may be addressed in future studies. The analysis was limited to storm-induced failure modes that are physically plausible for stationary LH_2 storage tanks. Consequently, the interaction among safety barriers was analysed while excluding "*sinking of floating roof*", which is not included in the design, as well as "*breach and overfill scenarios*", which is associated with mechanisms involving hydrocarbons in refinery applications.

The results reported in Table 3 illustrate how storm-related natural events may affect selected safety barriers representative of different safety functions, namely a preventive barrier belonging to the pressure relief systems macro-category, a mitigative barrier within the fire protection systems macro-category and a detection barrier associated with gas detection systems, covering complementary roles against hazardous conditions. Notably, the storm-induced failure modes considered are predominantly of a mechanical/physical nature. In this context, the analysis deliberately

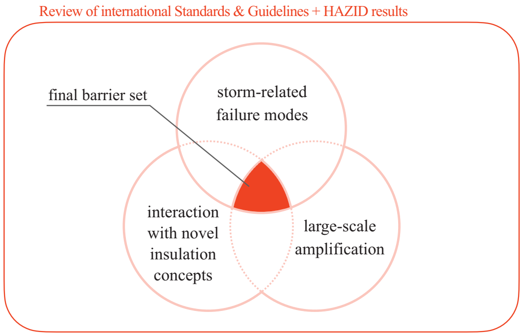

Fig. 1.: Conceptual illustration of the final safety barrier selection

focuses on damage mechanisms that are compatible with realistic storm scenarios and that allow for a meaningful assessment of safety barrier vulnerability. Extremely severe impact scenarios, such as the direct collision of large equipment or massive structural elements with safety-critical components were intentionally excluded, as they would lead to immediate and widespread system failure, making the analysis of individual safety barriers no longer informative. For the same reason, the study considers only safety barriers that are externally exposed to storm effects. Barriers whose failure would inherently imply a prior loss of primary containment, such as pressure safety valves (PSVs) located in the gap inside the tank, were not included. Finally, although storm events may occur in combination, they were analysed individually to preserve clarity and traceability of the failure mechanisms affecting each safety barrier and to enable a systematic comparison across different storm categories. Multi-hazard scenarios where therefore excluded, as they lie beyond the scope of the present study.

3.1. *Testing under representative storm conditions*

A first key aspect concerns the need for performance testing of safety barriers under representative environmental conditions. Many safety systems are tested under nominal or standardised conditions that may not fully capture the effects of strong wind, heavy precipitations or combined mechanical and electromagnetic disturbances. For large-scale installations, targeted testing or qualification campaigns that account for realistic storm-induced loads and boundary conditions may significantly improve confidence in barrier performance during extreme weather events. Existing standards and guidelines indicate that wind effects on safety barriers are generally addressed in an implicit or qualitative manner, rather than through dedicated performance testing. For example, in fire protection systems based on water spray or deluge, wind is explicitly recognized as a factor that can lead to water wastage, reduced spray effectiveness or unfavorable operating conditions for water curtains (NFPA (2017)). However, there is no mention of a quantitative acceptance criteria or mandatory performance testing under wind-exposed conditions. Minimum operating pressures are sometimes recommended to mitigate wind effects on spray patterns, yet system acceptance and functional verification remain largely based on tests conducted under only nominal conditions (NFPA (2022)). Similar considerations can be extended to other environmental stressors, such as heavy precipitations. For pressure relief devices, climatic and external mechanical actions, including wind, are addressed only qualitatively at the application/installation level, while performance and discharge capacity are verified through standardized test-bench procedures under nominal conditions (ISO (2019); ISO (2008)). Furthermore, LH_2 vent and relief systems should avoid exposure to water (including firewater) due to the risk of ice formation and vent clogging (Samdal et al. (2021)), an aspect that may be challenged under storm conditions but

Table 2.: Classification of main safety barriers for LH_2 storage systems

Macro-category	Safety barrier	Type
Containment	Physical protection structures (bollards, barriers)	Passive
	Secondary containment systems (bunds, catch basins)	Passive
Isolation and "safe condition"	Sectionalization capability (isolation valves)	Passive
	Shut-off and check valves	Active
	Emergency Shutdown System	Active
Pressure relief systems	Primary vessel pressure relief devices (PRDs)	Active
	PRDs for vacuum space (over/under pressure)	Active
	Burst disks (inner tank)	Passive
	Thermal relief devices	Passive
Blowdown, venting and discharge	Vent stack and discharge routing to safe location	Passive
Layout and ventilation	Open layout and elevation of equipment	Passive
	Natural ventilation	Passive
	Mechanical ventilation	Active
Ignition source control	Ex-rated equipment (Gas group IIC)	Passive
	Grounding and bonding	Passive
Process monitoring	Level shutdown interlock	Active
	Pressure monitoring	Active
	Temperature monitoring	Active
	Density monitoring	Active
	Flowrate monitoring	Active
Gas detection systems	Gas leak detectors	Active
	Acoustic leak detectors	Active
Fire protection systems	Fire detectors (thermal / optical)	Active
	Water cooling / deluge / foam systems	Active
Insulation-related safety	Getter materials for vacuum insulation spaces	Passive

is not addressed through performance testing. For detection systems, such as acoustic sensors, wind-related effects on signal reliability are largely outside the scope of current qualification frameworks. While tests under prescribed air velocity conditions may be included, these are intended to represent controlled airflow during laboratory testing rather than realistic wind-induced turbulence that may affect signal propagation (IEC (2025)). In contrast, significant emphasis is placed on electrical and electromagnetic robustness, including immunity to electromagnetic interference, whereas meteorological phenomena such as wind or heavy rain noise are not explicitly addressed.

3.2. *Post-event inspection and recovery preparedness*

Beyond performance during the storm event, the analysis highlights the importance of post-event inspection and recovery procedures. Storm-induced damage may not always result in immediate loss of functionality, but can lead to latent degradation mechanisms affecting safety-critical components, such as misalignment, seal damage, water ingress, icing or sensor drift. Dedicated post-storm inspection protocols are therefore essential before resuming normal operation.

Historical Natech analyses show that post-event inspection and recovery are frequently delayed by site inaccessibility, debris accumulation and power loss, allowing releases or escalation to continue well beyond the initiating event (Santella et al. (2010); NOAA (2025); Sutherland et al. (2018)). In addition, recovery-oriented design and operational preparedness, including the availability of spare skids or modular components, can significantly reduce the time required to restore safety functions after a storm event.

3.3. *Lightning*

Lightning-induced effects emerged as a particularly critical aspect across the addressed safety barriers. While grounding and lightning protection systems are commonly recommended as primary mitigation measures, recent studies suggest that grounding alone may not always be sufficient particularly when indirect lightning effects and induced overvoltages are involved (Rodriguez et al. (2024)). This is especially relevant for components such as pressure relief devices and sensors, whose functionality may be impaired even without a direct lightning strike.

Consistently with consolidated Natech statistics, the results of the present analysis confirm that lightning-related damage modes can simultaneously challenge preventive and mitigative measu-

Table 3.: Storm-induced degradation of selected safety barriers

Storm event	Consequences	Effect on the system	Recommendations
Water Cooling / Deluge / Foam Systems (WDS)			
Strong wind	• Mechanical damage to piping, supports, joints and nozzles due to wind loads and airborne projectiles • Wind-induced vibration and misalignment of spray devices • Dispersion and deflection of water/foam jets	• Partial or total loss of functionality • Reduced discharge capacity and non-uniform spray patterns • Inability to effectively reach target areas	• Orientable or shielded nozzles • Physical protection against airborne projectiles • Reinforced mechanical design of piping and supports
Heavy precipitation & flash flooding	• Ingress of debris, sediments and fine particulates into strainers, filters and pumps • Partial or total flooding of pump rooms and electrical cabinets • Rain/snow-induced icing of exposed components • Loss of electrical power supply to pumps and controls	• Loss of availability of the WDS • Delayed or failed system activation • Degraded and unstable water/foam delivery	• Installation of pumps and critical equipment in flood-protected or elevated areas • Redundant and protected power supply (e.g. diesel backup) • Inspectable upstream filters for debris management
Storm surge	• Partial or total submersion of pumps, piping and auxiliaries • Mechanical impact from floating debris • Pressure waves and slamming loads on piping and joints • Accelerated corrosion due to saline water exposure (if nearby costal areas)	• Partial or total loss of functionality	• Installation of critical components above design surge level • Reinforced supports and flexible joints to absorb dynamic loads • Use of corrosion-resistant materials and protective coatings
Lightning	• Direct lightning strikes or induced overvoltages on electrical equipment • Short circuits and damage to pump control systems • Thermal puncturing of metallic components	• Loss of control over pump start/stop • Unintended activation or failure to activate the WDS	• Lightning protection and grounding systems • Redundant and segregated control architectures
Re-closable pressure relief devices (PRDs)			
Strong wind	• Impact of airborne projectiles on PRDs and associated inlet/outlet piping • Wind-induced vibrations leading to fatigue or misalignment of flanged connections • Deformation of supports or roof-mounted joints	• Reduced discharge (pressure relief) capacity • Potential fail-open or fail-close conditions	• Physical protection against airborne projectiles • Reinforced mechanical design of piping and supports • Redundant PRDs with separated layouts
Heavy precipitation & flash flooding	• Water ingress into the valve seat and/or pressure sensing line • Rain/snow-induced icing of exposed components • Deposition of debris, sediments and fine particulates into the valve seat • Damage to electrical or pneumatic components	• Delayed or failed opening • Impaired reclosing capability	• Shielded and self-draining PRD housings
Storm surge	• Partial submersion of PRDs or connecting piping • Mechanical impact from floating objects • Pressure waves and slamming loads on piping and joints • Accelerated corrosion due to saline water exposure (if nearby costal areas)	• Loss of tightness or mechanical integrity • Delayed or failed opening • Impaired reclosing capability	• Installation of critical components above design surge level • Reinforced supports and anchoring systems to absorb dynamic loads • Use of corrosion-resistant materials and protective coatings
Lightning	• Direct lightning strikes or induced overvoltages damaging actuation or control systems of assisted PRDs • Thermal puncturing of metallic components	• Complete loss of PRD functionality	• Lightning protection and grounding systems • Use of passive PRDs indipendent of external power

(continued on the next page)

Table 3.: Storm-induced degradation of selected safety barriers (continued)

Acoustic sensors			
Strong wind	• Increased background noise generated by wind and turbulence • Wind-induced vibrations transmitted through piping and supports to sensor mounting points • sensor drift	• Reduced signal-to-noise ratio (SNR) • Potential false positive or missed detections • Degraded reliability of leak identification	• Mechanical decoupling and isolation of sensor mounts • Redundant sensor placement enabling cross-comparison and noise filtering
Heavy precipitation & flash flooding	• Direct impact of rain on exposed sensors or housings • Flooding of local power or signal transmission components • Rain/snow-induced icing of exposed components	• Signal distortion or attenuation • Malfunction or failure of sensor electronics • Partial or total loss of availability of the detection function	• Use of weatherproof and watertight sensor housings • Elevated installation of sensors and cabling where feasible • Drainage and shielding to limit direct water impingement
Storm surge	• Partial or total submersion of sensors and associated cabling in coastal installations • Mechanical impact from floating objects • Pressure waves and slamming loads on components	• Partial or total loss of availability of the detection function	• Installation of sensors above design storm surge level • Protective housings and mechanical guards against debris impact
Lightning	• Direct lightning strikes or induced overvoltages damaging sensor electronics or power supply • Electromagnetic interference affecting sensor signals	• Signal corruption • Partial or total loss of availability of the detection function	• Lightning protection and grounding systems

res, reinforcing the need for barrier lightning protection strategies.

3.4. *Redundancy*

Although redundancy is generally considered a robust safety strategy, its effectiveness under storm-related events deserves careful consideration, especially in the context of large-scale LH_2 storage systems. Due to the large inventories involved, such installations typically would rely on multiple and redundant pressure relief devices to ensure adequate venting capacity under abnormal pressure conditions.

However, the presence of multiple PRDs and associated piping networks increases system complexity and exposure to external stressors. Under storm conditions, this may lead to common-cause failures or unintended interactions, potentially reducing the overall effectiveness of the relief system. Recent analyses of hydrogen incidents have shown that PRDs can themselves become sources of leaks or releases, with spurious activations and high upstream inputs among the most frequently observed failure modes (Jimenez and Groth (2024)).

In this context, redundancy should not be regarded as a standalone safeguard, but rather complemented by appropriate layout design, physical separation, diversification of relief devices and protection against common external stressors. This aspect is particularly relevant for large-scale LH_2 storage systems, where high boil-off rates and demanding venting requirements amplify the consequences of PRDs malfunction or their unintended activation.

4. Conclusions and Future Directions

This work investigated the vulnerability of selected safety barriers for large-scale liquid hydrogen (LH_2) stationary storage systems under storm-induced Natech conditions, through a What-If analysis focused on three safety barriers, each representative of preventive, mitigative and detection functions, respectively. The results highlight that storm-related natural events can compromise safety barrier functionality primarily through mechanical and physical damage mechanisms, even in the absence of catastrophic structural failure. In this context, storm resilience can not rely solely on the presence of safety barriers, but also depends on their ability to maintain functional performance during and after extreme weather events, as well as on effective post-event inspection and recovery strategies.

Future work may address additional safety barriers that were not included at this stage and perform more detailed investigations to identify further storm-related failure modes and hydrogen-specific degradation mechanisms that are not yet systematically accounted for in current Natech frameworks.

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