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Natech Risks in Hydrogen Repurposed Pipelines: Triggering Events, Vulnerabilities, and Mitigation Strategies

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The use of clean hydrogen to decarbonize hard to abate sectors has been under consideration in the context of the global energy transition, and repurposing natural gas pipelines has emerged as a cost-effective option for hydrogen transport. While this approach leverages existing infrastructure, it also introduces safety challenges, one of them being new weaknesses in natural hazard triggered technological (Natech) accidents. This paper provides a theoretical framework to understand Natech risks in hydrogen repurposed pipelines by identifying the main triggering events, highlighting the specific vulnerabilities of hydrogen compared to natural gas, and outlining mitigation strategies. The study reviews academic literature to select and analyze relevant natural hazards affecting Europe that can initiate pipeline failures. Hydrogen's characteristics, such as its wider flammability range, lower ignition energy and propensity for material embrittlement, amplify both the probability of release and the severity of consequences. The paper draws on strategies from structural and organizational risk reduction to examine targeted accident prevention and mitigation measures. By mapping hazard-vulnerability-mitigation linkages, this paper aims to support operators, regulators, and researchers in developing more resilient hydrogen transport networks. The findings emphasize that hydrogen's distinct physical and material interactions require dedicated risk reduction strategies.

Keywords: Natech risk, Hydrogen pipelines, Natural hazards, Risk reduction, Accident scenarios, Floods, Landslides, Lightning, Cold wave.

1. Introduction

Clean hydrogen has been assessed as an energy carrier capable of complementing electrification in the energy transition. Its use can address the problem of mismatch between energy supply and demand generated by the increased installation of intermittent renewable power, as well as providing long duration storage, enabling sector coupling, and supporting deep decarbonization of hard to abate sectors (Odenweller and Ueckerdt, 2025). Despite the recent slowdown in the ambition of clean hydrogen projects, long-term energy scenarios still project substantial growth in hydrogen production over the coming decades (IEA, 2025). As a result, the availability of large-scale, reliable and economically viable transport infrastructure becomes a critical prerequisite for system integration (IEA, 2025). An example of the commitment to establishing transport infrastructure is the European Hydrogen Backbone (EHB) initiative. It proposes five major supply corridors connecting regions such as North Africa, the North Sea, and the Baltic countries to European demand industries (EHB, 2023). Among the various transport options, pipelines remain one of the most promising technologies capable of moving large amounts of gaseous hydrogen over long distances at competitive cost (Great Plains Institute, 2024). Three main strategies are currently considered for hydrogen pipeline development, all of them with different advantages and disadvantages:

- Building new pipelines allows optimization of materials, diameters, and pressure ratings for hydrogen service. However, they require substantial capital investment and lengthy permitting (DNV, 2023).
- Pilot projects have demonstrated the technical feasibility of blending small amounts of hydrogen into natural gas (NG) systems. But above roughly 20% $_{vol}$, material performance, compressor behaviour, gas quality constraints, and regulatory limits pose growing challenges (Islam et al., 2024)
- Repurposing NG transmission pipelines to 100% hydrogen offers a potentially rapid and cheaper scale-up pathway by leveraging existing infrastructure (EHB, 2024, DNV, 2023), but this approach also has important challenges to address, like hydrogen embrittlement and increased leakage risk or the lower energy density issue (Martin et al., 2024).

An emerging area of concern is the resilience of these repurposed pipelines against natural hazard triggered technological (Natech) accidents. While an existing natural gas pipeline may be designed to withstand standard operational stresses and certain natural hazards, the introduction of hydrogen changes the material's response to stress. Repurposed pipelines' safe limits need to be assessed not only under normal operating conditions, but under high-stress scenarios such as floods or landslides. Since the degradation of the mechanical properties of the pipeline's material caused by hydrogen embrittlement could lead to accidents that would not occur transporting NG.

This study aims to bridge the knowledge gap and lay the groundwork for future investigations into Natech risks in hydrogen pipelines. Emphasis is placed on repurposed pipelines, as they present the highest risk profile. However, the findings are also applicable to newly built systems. The rest of the paper presents the systematic Natech risk assessment framework which was followed to identify relevant natural hazards and discuss the implications of hydrogen-specific vulnerabilities on consequences and risk reduction measures.

To ensure a systematic evaluation of the risks associated with repurposing NG pipelines for hydrogen service, this study adopts concepts and frameworks extracted from standards and authorities in the field. It starts with the Risk Management framework outlined in the ISO 31000 standard (ISO, 2018), which defines the risk assessment process as comprising three main stages:

- Risk identification, which consists of finding, recognizing, and describing risks that might affect the system.
- Risk analysis, where the nature of the risk is comprehended and its level determined.
- Risk evaluation, where the estimated risk is compared against pre-established criteria.

While this general procedure is widely applied across various industries, when the focus is specifically in Natech accidents, risk assessment lacks a standardized methodology. Nevertheless, several quantitative risk assessment (QRA) frameworks tailored to specific natural hazards are documented, as well as emerging multi-risk approaches attempting to integrate cascading natural and technological threats (Sorichetti et al., 2022). Moreover, dedicated software tools have been developed to support the QRA of Natech scenarios (Krausmann et al., 2017).

2. Methodology

With the development of this paper, different aspects of the three stages of risk assessment will be addressed. As shown in Figure 1, the methodological approach is structured into the following phases:

- Step 1) Hazard Identification and Analysis: the study begins by identifying the main natural hazards relevant to the European infrastructure. The hazard classification is based on the Peril Classification and Hazard Glossary, which groups hazards based on their origin into families: geophysical, hydrological, meteorological, climatological, extraterrestrial and biological (IRDR, 2014). The latter two will be excluded due to their lower frequency and limited relevance to the topic. The data from the EM-DAT was analyzed to filter hazards based on their frequency in EU and their impact on pipeline system, spanning the period from 2000 to 2025 (CRED, 2024).

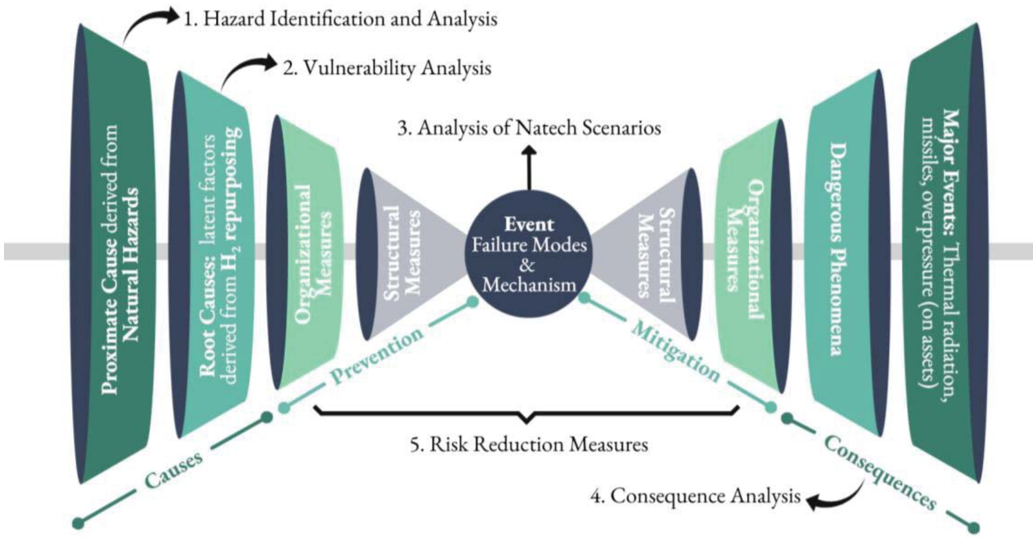

Fig. 1. Five-step methodology approach, which ensures that different dimensions of Natech risks are addressed

- Step 2) Vulnerability Analysis: Examine how hydrogen service change pipeline material properties compared to natural gas, focusing on hydrogen embrittlement mechanisms and its influence on the structural integrity under natural loads.
- Step 3) Analysis of Natech Scenarios: Explore synergies between natural hazards and hydrogen specific vulnerabilities to define credible accident scenarios that would not occur under natural gas service.
- Step 4) Consequences Analysis: Assess the severity of potential failures involving hydrogen releases, considering hydrogen's physical and chemical properties and their implications for escalation.
- Step 5) Risk Reduction Measures: Structural and organizational measures for prevention and mitigation strategies are proposed.

To avoid overlapping terminology, we adopt the definitions established in the international standard ISO 14224 for the petroleum and gas industries (ISO, 2016). Accordingly, 'failure mode' is defined as the observable loss of function of the component (e.g., rupture or leakage), while the 'failure mechanism' refers to the physical, chemical, or thermodynamic process inducing the mode, such as hydrogen embrittlement or fatigue. Regarding causality, it is distinguished between the 'proximate causes', defined as the immediate triggering event (e.g., the natural hazard load), and the 'root causes', which encompass the latent systemic vulnerabilities (CCPS, 2019).

3. Analysis and Discussion

3.1. *Identifying and Analyzing the Main Natural Hazards in EU*

Gathering and processing data for natural events in Europe (CRED, 2024), it reveals a hierarchy in terms of frequency and economic impact. Floods constitute the most frequent and costly hazard family in Europe, accounting for 490 recorded events and over 173 billion dollars in total damage. This is followed by storms (373 events) with broad geographic coverage and extreme temperatures (322 events) with seasonal certainty and increasing intensity. However, frequency alone does not dictate pipeline risk. While landslides (mass movement) show a lower frequency in the general database (19 events), the technical report *Analysis of pipeline accidents induced by natural hazards* by the Joint Research Center identifies geological hazards as the dominant category for Natech pipeline accidents, with landslides constituting the primary failure mechanism within this subgroup, followed by subsidence and seismic events are relegated to a minor cause, among others (Girgin and Krausmann, 2014).

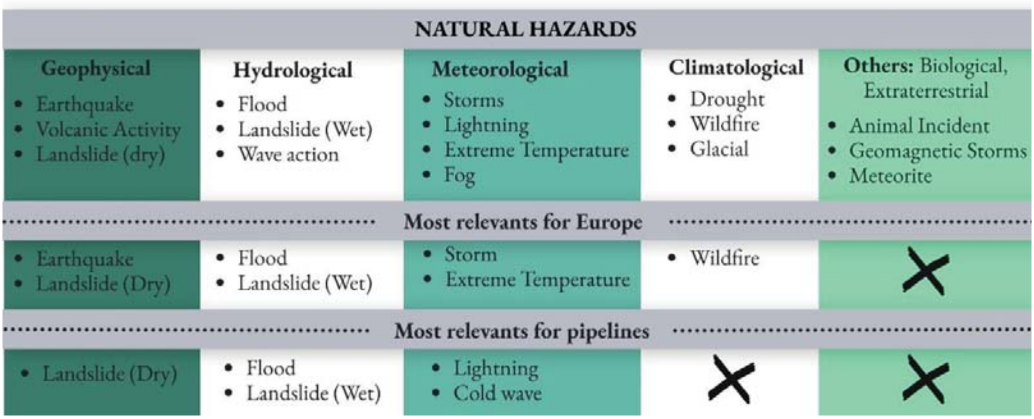

Fig. 2. Selection of the most relevant natural hazards for repurposed hydrogen pipelines in Europe.

Similarly, while lightning causes low structural damage, it dominates meteorological incidents affecting pipeline operations, and cold waves account for the major portion of climate related infrastructure failures (Girgin and Krausmann, 2014). Consequently, based on the intersection of European recurrence rates and pipeline specific severity, this study isolates four priority hazards for the hydrogen repurposing analysis: floods, mass movement (landslides, subsidence), cold waves, and lightning. The selection process followed is shown in Figure 2. Once the most relevant natural hazards for this study have been localized, it is possible to analyze them more in depth.

3.1.1. *Hazard Analysis: Floods*

Different types of floods exist, each with their own characteristics. Riverine floods are characterized by a gradual rise in water levels, while flash floods involve rapid arrival and high velocity flows, often carrying significant debris. Coastal floods introduce an additional factor of wave action and salinity (NOAA).

In the context of hazard assessment, a key factor to consider is whether the pipeline was built above or below ground, since the soil cover acts as a protective shield and the natural hazards impact will be different (Lanzano et al., 2014).

The primary threat to the pipeline does not always come from the water's presence, but from the specific load induced. According to literature on buried infrastructure (Abegaz et al., 2024), these loads are divided into:

- Hydrostatic loads (buoyancy): This is the vertical upward force applied by the displaced fluid. For NG and H_2 pipelines, which are significantly lighter than pipes filled with liquid, the buoyancy force can exceed the weight of the pipe and soil cover.
- Hydrodynamic loads: Once water begins to flow around a pipe, it creates drag forces and lift forces, the first pushes the pipe downstream, and the second, pulls the pipe upward perpendicular to the flow.
- Impact loads: In some scenarios, the kinetic energy of debris striking the pipeline constitutes a distinct load category.

The interaction between these loads and the pipeline triggers critical failure mechanisms. These include scouring, where soil erosion removes structural support, leaving the pipeline in a free-spanning state. This exposure makes the pipeline vulnerable to Vortex-Induced Vibrations (VIV), which generate stress cycles leading to rapid fatigue failure (Ariaratnam et al., 2021). Furthermore, in saturated soils, buoyancy forces can induce upheaval buckling, forcing the structure toward the surface and causing plastic deformation. Finally, debris impact could cause immediate pipeline rupture or the formation of 'hard spots' that facilitate corrosion and lead to future pipeline failure (Ghadiani et al., 2024).

3.1.2. *Hazard Analysis: Mass Movement (Landslides, Subsidence)*

There are several types of mass movements described in the report *Management of Ground Movement Hazards for Pipelines* (INGAA, 2017). The most critical types for pipelines are translational slides which are a planar movement along a slip surface, and rotational slides, characterized by a curved slip surface. Rockfalls pose a distinct threat to above ground facilities but rarely affect buried lines. Soil creep represents a slow, continuous hazard that accumulates stress over years. The primary load is Permanent Ground Deformation (PGD). Unlike transient loads, mass movements impose a displacement load, moving the soil and forcing the pipeline to conform to its new geometry (INGAA, 2017).

This deformation manifests as either longitudinal PGD, where parallel soil movement creates axial tension or compression, or transverse PGD, which imposes perpendicular bending and shear forces. Depending on the strain direction, the pipeline orientation relative to the slide and the pipeline material, these loads can lead to tensile rupture, which occurs when the pipe is stretched beyond its limits, or local wrinkling and global buckling induce by compressive forces, often resulting in loss of containment if the deformation causes cracks (INGAA, 2017).

3.1.3. *Hazard Analysis: Lightning*

Lightning threats can be categorized into direct strikes if there is physical contact with the structure, or indirect effects caused by a nearby strike. For pipeline networks, the threat can be further divided into impacts on venting systems and impacts on control systems. The proximate cause of lightning is the transfer of massive electrical energy and the generation of heat. Unlike other hazards, lightning rarely causes structural rupture of the pipe, but it can cause vent stack ignition, Supervisory Control and Data Acquisition (SCADA) failures or coating damage if the strike blows a hole in the pipeline’s anti-corrosion coating (IEC, 2010, Necci et al., 2016, Renni et al., 2010).

3.1.4. *Hazard Analysis: Cold Waves*

Cold hazards manifest as ambient low temperatures and ground freezing. The duration is critical, since a prolonged deep freeze can alter the soil mechanics. These conditions impose severe physical loads, such as thermal contraction, which generates longitudinal tensile stress in restrained pipes, and frost heave, where the expansion of freezing water in wet soils creates upward forces that lift the pipeline (Owu, 2025). Furthermore, the pipeline material degrades as temperatures drop below the Ductile-to-Brittle Transition Temperature (DBTT), causing the steel to lose its plastic deformation capabilities and become brittle. This effect is worsened in repurposed pipelines, as hydrogen embrittlement raises the DBTT, making the steel brittle at higher temperatures than usual (San Marchi and Somerday, 2012).

3.2. *Specific vulnerabilities of hydrogen compared to natural gas*

To understand how hydrogen can change the Natech risk profile of NG pipelines, the degradation mechanisms should be analyzed at a microscopic scale. Unlike CH_4, atomic hydrogen diffuses into the steel lattice, triggering hydrogen embrittlement and changing critical material properties (Dwivedi and Vishwakarma, 2018):

- Reduction in ductility: Mechanisms like Hydrogen-Enhanced Localized Plasticity (HELP) and Hydrogen-Enhanced Decohesion (HEDE) cause a transition from ductile to brittle behavior (San Marchi and Somerday, 2012). This drastically reduces the Tensile Strain Capacity (TSC), meaning a pipeline subjected to some Natech loads may break rather than deform.
- Reduced fracture toughness: Hydrogen lowers the threshold stress intensity factor, meaning the that the critical crack size for unstable rupture is smaller. Therefore, small defects harmless in NG service may propagate under hydrogen atmospheres.
- Accelerated fatigue crack growth: Hydrogen accelerates crack growth rates by up to two orders of magnitude, depending on material, environmental, and mechanical factors (San Marchi and Ronevich, 2022). Consequently, cyclic loads from hazards like flood induced vibrations can rapidly propagate cracks and reduce the pipeline's fatigue life.
- Ultimate tensile strength: While the yield remains largely unchanged, the margin between yield and ultimate tensile strength reduces, leading to sudden rupture without warning signs (San Marchi and Somerday, 2012).

It is important to note that susceptibility is dependent on several operation parameters. Factors such as H_2 blend percentage, operating pressure, and line packing pressure cycles can worsen fatigue crack growth rates if the operation is not well optimized, further reducing the pipeline's resilience to external Natech loads. Another challenge lies in the regulatory gap. Unlike new H_2 pipelines designed under ASME B31.12, which mandates strict stress limits and material toughness requirements to account for embrittlement, existing NG pipelines were designed according to ASME B31.8, which allows for design factors that may not be conservative enough for H_2 service when pipelines are exposed to the additional external loads of natural hazards (ASME, 2022, ASME, 2023).

3.3. *Analysis of Natech Scenarios: Synergies*

The core finding of this study is that the interaction between natural hazards and hydrogen service is not additive, but synergistic. As illustrated in Figure 3, specific natural hazard loads can activate degradation mechanisms that would remain dormant or manageable in conventional NG service. This interaction significantly increases the probability of failure.
For instance, in the case of a landslide, the lower TSC of the steel induced by hydrogen may cause a ground displacement, that would be tolerable for NG pipelines, to exceed the admissible strain limits in hydrogen service, potentially leading to rupture or weld failure. Similarly, lightning represents more than just a thermal hazard. As indicated in Figure 3, high voltage arc contact and the localized heating followed by a rapid cooling can induce local hardening and facilitate hydrogen trapping in the microstructure. These localized defects can become crack initiation sites, transforming a momentary strike into a latent structural threat.

3.4. *Consequence Analysis: Amplified Severity*

The Natech risk profile for repurposed pipelines is defined not only by the increased probability of failure under natural hazard loads but may also result in amplified consequences in certain post-release scenarios. The consequences of accidental release depend upon hydrogen's physical and chemical properties.
Hydrogen exhibits a significantly wider flammability range compared to methane. More critically, its Minimum Ignition Energy (MIE) is one order of magnitude lower than that of methane (Massarweh et al., 2025), increasing the risk of combustion from minor leaks. While hydrogen's low density allows for rapid vertical dispersion in open areas, it presents a severe hazard in confined geometries (Cirrone et al.,

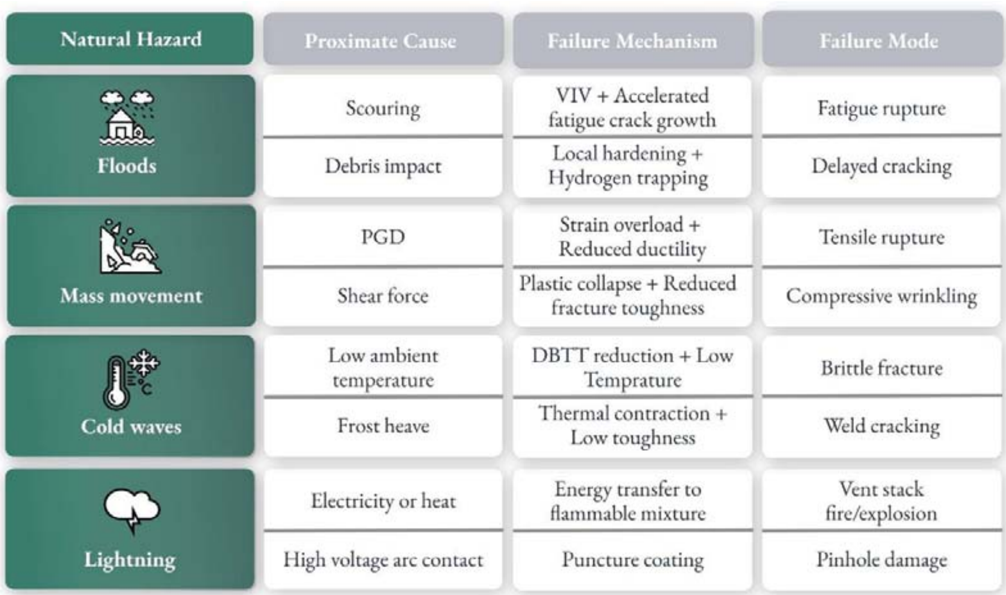

Fig. 3. Interactions between natural hazards and hydrogen vulnerabilities.

2019). Collectively, these factors highlight that hydrogen pipeline failures, when they occur, can lead to more severe and faster-developing events compared to conventional NG systems (Smedberg et al., 2025).

3.5. Natech Risk Reduction Measures

To address these risks, it is crucial to develop a tailored risk reduction strategy. Measures can be classified based on their objective: prevention, for measures acting before the event to reduce the likelihood of damages or hazardous releases, and mitigation measures, which act after a release has occurred, their goal is to reduce the impact and prevent escalation. Both dimensions are essential to build a complete Natech risk reduction strategy (Krausmann et al., 2017). Furthermore, the measures can be classified based on their nature: where structural measures are engineering-based protections such as anchoring, barriers, flexible connections, or coatings. And organizational measures are based on management actions like maintenance programs, emergency procedures, training, and safety governance frameworks (Krausmann et al., 2017).

4. Conclusions

This study shows that repurposed hydrogen pipelines can face amplified Natech risks due to hydrogen's unique properties and their interaction with natural hazards. Floods, mass movements, lightning, and cold waves emerge as priority hazards, and hydrogen embrittlement significantly increases failure probability and severity. Effective risk reduction requires combined structural and organizational measures.

This study is exploratory in nature, and the findings are qualitative. Future research should therefore focus on geospatial analysis, mapping the planned pipelines against regional natural hazard zones to identify critical hotspots, developing quantitative multi-hazard risk models for hydrogen pipelines, establishing tailored risk reduction strategies, and investigating advanced monitoring systems for early detection of interactions between degradation and hazard.

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