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REVIEW

Hydrogen Blending in Natural Gas Networks: Embrittlement-Induced Leakage as a New Threat to Hydrogeological Integrity

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ABSTRACT

The concept of hydrogen mixing into the pre-existing natural gas systems is a more and more actively encouraged approach to the decarbonization of the near term, but its integrity concerns go well beyond the traditional pipeline safety and subsurface environmental statement. This review summarizes existing information about hydrogen-material interactions in existing gas infrastructure and presents the leakage that occurs as a result of embrittlement as a new threat to hydrogeological integrity. We initially look at the processes involved in hydrogen ingress weakening metallic and non-metallic elements, and we mainly focus on how microstructural trapping, residual stress, weld heterogeneity, and pressure cycling accelerate crack initiation and subcritical crack propagation. We next consider how these degradation mechanisms can be converted to more diffuse and sustained leakage pathways than the more normal methane-based failures, and hydrogen is more likely to escape via microdefects and broken seals. The review also evaluates what happens to leaked hydrogen in soils and aquifers, and shows that it is highly mobile and capable of altering redox conditions, inducing hydrogenotrophic microorganisms to grow, and affecting the mobility of elements and co-contaminant redox-sensitive elements. Mixed scenarios of leakage of hydrogen and methane are considered as compound hazards, making it difficult to detect, attribute, and assess the risk. Lastly, we list the major gaps in research and governance, such as the necessity to have blended-gas embrittlement data in realistic operating conditions, hydrogen-sensitive leakage identification in buried infrastructure, and correlated transport reaction models, which relate the evolution of leakage to the effects of groundwater. In assuring decarbonization through hydrogen

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blending, a material-hydrogeology approach will be crucial to avoid any unintended effects of carbon on the subsurface environment.

Keywords: Hydrogen Blending; Hydrogen Embrittlement; Pipeline Leakage; Groundwater; Subsurface Biogeochemistry

1. Introduction

Decarbonization of energy systems has increased the pace at which the world has shown interest in hydrogen as a low-carbon energy carrier that can supplement renewable electricity and mitigate the emission of greenhouse gases in hard-to-abate sectors [1–5]. Deployment of hydrogen into existing natural gas networks is one of the many deployment pathways that have become appealing as a near-term solution due to its potential use of existing infrastructure and avoidance of the upfront expenses of specific hydrogen pipelines. Hydrogen can be injected into natural gas transmission and distribution systems at mixing ratios usually ranging from a few percent to 20% by volume, with only small changes to end-use appliances in some cases, as shown in pilot projects and early commercial deployments. Hydrogen blending is therefore being presented more and more as a pragmatic step towards the present-day fossil-based gas systems and the proposed hydrogen economy in the future [6].

Nevertheless, the addition of hydrogen to existing gas infrastructure presents us with material and environmental issues that are entirely distinct from those related to methane-containing systems. The molecular size of hydrogen is small, there is great diffusivity, and interaction with metals, which concerns infrastructure durability, safety, and leakage. Although the technical feasibility of hydrogen blending has been a well-regarded issue in the context of combustion performance, the energy content, and the compatibility of hydrogen with additional components, the long-term durability of the pipelines and other ancillary elements under hydrogen conditions is not adequately studied, especially through an environmental risk prism [7,8].

One of the issues herein would be hydrogen embrittlement, a degradation process in which the ingress of hydrogen into metallic materials results in ductile loss, fracture toughness loss, and an increase in crack initiation and propagation [9]. Most existing natural gas transmission and distribution networks contain a high proportion of carbon steels and low-alloy steels, and these are known to be prone to many types of damage caused by hydrogen. These comprise hydrogen-enhanced localized plasticity, hydrogen-induced cracking, and decohesion mechanisms that can have a major impact on failure behavior. Despite numerous investigations of hydrogen embrittlement in materials science and mechanical engineering, its implications and effects on the development of gas leakage at blended hydrogen-methane conditions have not been fully amalgamated.

The majority of current research on hydrogen blending pays attention to the integrity of the pipeline through an engineering reliability lens, and it is much more concerned with the reduction of burst pressure to reduce the fatigue life of the pipeline or fracture mechanics under controlled laboratory situations. These studies are very insightful, but they tend to regard leakage as a minor consequence rather than a major risk. Practically, microcracking enhanced by embrittlement, seal wear, and permeability rise can be used to allow chronic and low-rate leakage, instead of catastrophic failure. These leakage cases are especially applicable to buried pipelines when the gas leakage will go undetected for long durations [10,11].

In addition to infrastructure safety and energy wastage, the hydrogen leakage adds a significantly neglected aspect of the environment, particularly when it comes to underground and groundwater systems [12]. The natural gas networks are deeply penetrated into soils, sediments, and fractured geological media, which tend to intersect shallow aquifers and environmentally sensitive areas. Leakage caused by material degradation due to hydrogen thus not only presents a technical integrity problem, but also be at risk to hydrogeological integrity. In contrast to methane, hydrogen will have different transport properties in porous media; it is highly diffusive, has high mobility, and is tightly coupled with microbial and geochemical processes.

According to the emergent studies, hydrogen, which may escape into the subsurface, can modify redox conditions, induce hydrogenotrophic microbial metabolism, and cause movement of redox-sensitive elements. Such processes can have indirect impacts on groundwater quality, such as changing biogeochemical equilibrium, which can either mobilize contaminants or change natural attenuation pathways. In addition, the case of hydrogen leakage can be parallel to that of methane release, and this represents coupled gas plumes whose environmental characteristics cannot be inferred by studying methane alone. In spite of these issues, the hydrogeological effects of hydrogen leakage have not been addressed seriously in hydrogen blending risk management, regulatory frameworks, and infrastructure planning strategies [13–15].

The originality of the current review is in the direct connection of hydrogen embrittlement, leakage development, and hydrogeological risk to a single conceptual framework. Instead of considering material degradation and environmental impact as two independent fields, the article explains that the leakage of embrittlement is a new, cross-cutting risk that needs to be considered at the overlap of materials science, pipeline engineering, and subsurface hydrology. These combined visions will be vital to decarbonizing projects as hydrogen blending increases beyond pilot projects to massive blending as it becomes more widespread across the country [16,17].

The other difficulty that is also discussed in this review is the lack of correlation between current monitoring practices and hydrogen leakage behavior specificity [18]. Piping integrity management systems that are based on conventional methods are designed to be optimized to detect methane, monitor pressure losses, and perform episodic inspection regimes. The nature of hydrogen has a tendency to be detected by the ability of hydrogen to diffuse deeply and leak through microdefects in low volumes, which makes it difficult to detect, especially in the subsurface setting. That is why this brings up the issue of late leak detection and the extended stay of soils and groundwater in contact with hydrogen and other related gases. Hydrogeologically speaking, even minor, yet consistent, fluxes can be enough to bring about significant biogeochemical change with time.

Although the problem of hydrogen leakage is increasingly being taken into consideration as an important climate-relevant concern, since hydrogen is an indirect cause of the greenhouse effect through its atmospheric chemistry, its impacts on the environment on a subsurface level are not fully explored [19,20]. Current environmental risk assessments on gas pipelines are mostly based on decades of experience with methane and fail to reflect the processes that are unique to hydrogen. The lack of such knowledge is especially troublesome in areas where the pipelines are old, geological conditions are not homogeneous, and the dependence on ground-based water is significant.

Accordingly, the objectives of this review are threefold. **Figure 1** provides a systems-level conceptual overview linking hydrogen blending, embrittlement-driven integrity loss, leakage evolution, and downstream hydrogeological consequences. To begin with, it is a synthesis of existing knowledge of the hydrogen-material interactions of interest to natural gas infrastructure, and specifically blended gas embrittlement mechanisms. Second, it looks at the way embrittlement becomes tantamount to leakage paths and failure modes with distinctly different qualitative characteristics than those found in traditional natural gas systems. Third, it critically examines the possible consequences of such leakage on the hydrogeological integrity with an emphasis on subsurface transportation, biogeochemical, and regulatory blind spots [11,21,22].

The review seeks to showcase to researchers, infrastructure operators, and policymakers the system-level risks of hydrogen blending by synthesizing the findings of literature related to separate topics. Finally, the issue of leakage caused by embrittlement should also be considered as an engineering and environmental issue in order to responsibly implement hydrogen into the current gas networks. Preemptively resolving this problem will enable making sure that hydrogen blending does not serve as a danger to climate reduction or undermine the subsurface environmental protection or the trust that the population has in the energy transition.

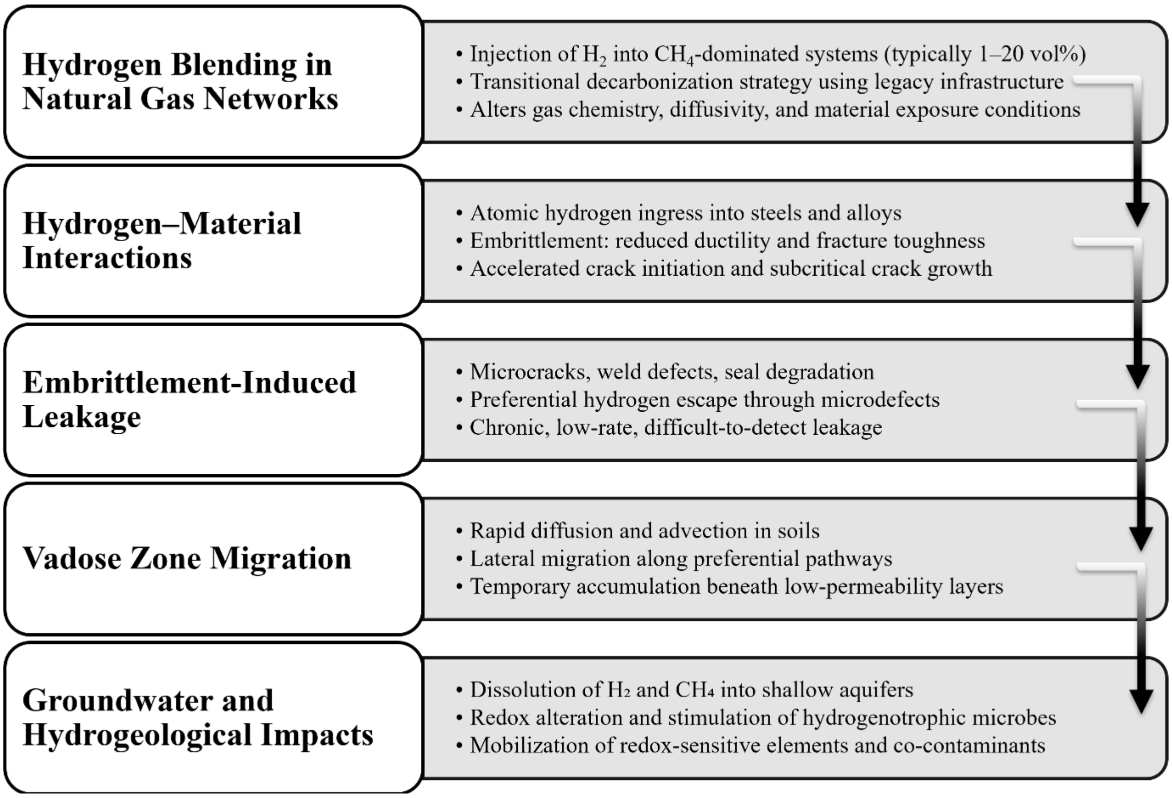

Figure 1. Conceptual coupling of hydrogen blending, embrittlement-induced leakage, and hydrogeological integrity.

2. Hydrogen–Material Interactions in Natural Gas Infrastructure

Hydrogen addition to natural gas systems fundamentally changes the physicochemical natural environment of pipeline materials and other related elements. In contrast with methane, hydrogen easily reacts with metals at the atomic level, including in microstructures, altering their mechanical behavior in a manner that cannot be well explained within the sight of traditional gas infrastructure design considerations. The study of such hydrogen material interactions is thus critical in the evaluation of the integrity of the existing networks when operating on blended gas and also in predicting the degradation paths that can cause leakage [17,23].

2.1. Material Composition of Existing Gas Networks

A majority of natural gas transmission and distribution systems around the world are made out of carbon steels and low-alloy steels, with the application grade of materials depending on the time of construction, the pressure rating, and the regulatory standards during construction. Elderly transmission pipes usually use steels of quite high impurity content, coarse microstructures, and sporadic quality of the welds; distribution networks may contain a combination of steel, cast iron, and polymeric materials. Other material heterogeneity and stress concentration locations are caused by ancillary parts like valves, flanges, compressors, and welded joints [24].

These materials have been chosen and found to qualify mostly for methane service, where chemical inertness and comparatively high molecular weight restrict the gas-metal interactions. The appropriateness of these legacy materials becomes less predictable when a hydrogen element is added, even in moderate proportions. **Table 1** presents typical materials and components of natural gas networks and emphasizes hydrogen-related vulnerabilities that possibly control leakage vulnerability during services with blended gases. Grain structure, dislocation density, inclusion morphology, and remaining stress field differences have a significant impact on the hydrogen uptake and damage evolution, resulting in spatially heterogeneous degradation along the pipeline systems [25,26].

Table 1. Representative materials and components in natural gas networks and hydrogen-relevant vulnerability.

Asset/Component	Common Legacy Materials	Typical Service Context	Hydrogen-Relevant Vulnerability	Likely Integrity Outcome under Blending
Transmission line pipe	Carbon steel, low-alloy steel	High pressure, long distances	Embrittlement susceptibility depends on grade, microstructure, and residual stress.	Subcritical crack growth; elevated fracture risk
Distribution mains (legacy)	Steel, cast iron (older)	Lower pressure, dense urban routing	Defects, corrosion history, joint weakness, cast iron brittleness	Joint leakage; crack propagation near stress raisers
Girth welds/weld zones	Weld metal + HAZ	Fabrication/repair locations	Heterogeneous microstructure; residual stresses; hydrogen trapping	Crack initiation/propagation at weld toe/HAZ
Flanges/fittings	Steels, stainless alloys	Interfaces, maintenance points	Stress concentration; gasket dependence	Local leakage, especially under cycling
Valves/regulators	Mixed metals + elastomers	Control nodes	Seal permeation; mechanical wear	Persistent low-rate leakage
Seals/gaskets	Elastomers, polymers	Joints, valves, meters	Permeation, swelling, blistering (rapid decompression effects possible)	Loss of tightness; diffuse leakage
Metering/service connections	Mixed materials	Customer interface	Many interfaces, aging, and installation variability	Frequent small leaks, difficult localization

2.2. Mechanisms of Hydrogen Embrittlement under Blended Gas Conditions

Hydrogen embrittling involves a collection of destruction processes in which hydrogen decreases the burden-carrying ability, as well as the fracture toughness, of metals [27]. On the most basic level, the hydrogen molecules are dissociated at the metal interfaces and diffuse into the lattice as atomic hydrogen. Hydrogen can also be trapped in the interfaces and at dislocations, grain boundaries, inclusions and phase interfaces within the material at the microstructural level once within the material. These trapped hydrogen atoms interact with local stress fields and alter deformation and fracture processes.

Several embrittlement mechanisms have been suggested to describe hydrogen-induced degradation in steels, such as hydrogen-enhanced localized plasticity, hydrogen-enhanced decohesion, and pressure-driven void formation [28,29]. Although the proportion of contribution of each of these mechanisms is still a topic of discussion, their overall impact is a decrease in ductility, increased crack initiation, and increased crack propagation in both static and cyclic loading. At the hydrogen partial pressures where hydrogen partial pressures are much less than in pure hydrogen systems, these mechanisms can occur, and there are concerns that after long-term exposure, even in low ratios of blending. **Table 2** integrates the prevailing embrittling actions suggested in the pipeline steels and contours them to the control of micro structural aspect and operating parameters that are especially pertinent in blended-gas networks.

Table 2. Hydrogen embrittlement mechanisms and controlling variables relevant to blended-gas service.

Mechanistic Class	Brief Physical Description	Typical Microstructural Hot Spots	Operating Variables That Intensify Risk	Practical Implication for Gas Networks
Hydrogen-enhanced localized plasticity (HELP)	Hydrogen facilitates dislocation motion and strain localization	High dislocation density regions, HAZ, cold-worked zones	Higher hydrogen partial pressure; cyclic loading	Earlier crack initiation under fatigue
Hydrogen-enhanced decohesion (HEDE)	Hydrogen reduces cohesive strength at interfaces	Grain boundaries, inclusions, phase interfaces	Tensile stress; stress triaxiality; low temperature (often)	Intergranular cracking; reduced toughness
Hydrogen-induced cracking (HIC)/blistering (where relevant)	Hydrogen accumulates at traps, forming internal pressure damage	Inclusions, laminations, segregated bands	Material cleanliness; trapping density; exposure duration	Internal damage that can be linked to through-wall defects
Trap-controlled diffusion and accumulation	Hydrogen migrates and concentrates in “traps”	Dislocations, precipitates, and weld defects	Aging, microstructure, residual stress fields	Strong location dependence of damage
Fatigue–hydrogen synergy	Hydrogen accelerates crack growth per cycle	Weld toes, corrosion pits, notches	Pressure cycling frequency/amplitude; variable load histories	Shift toward chronic crack growth and leakage

Notably, the presence of hydrogen embrittlement does not always show itself in the form of sharp, decisive breakage. On the contrary, it can tend to favor subcritical damage build-up, in which microcracks form and creep gradually over long intervals. This gradual deterioration is especially pertinent in the case of buried pipelines since the operation stresses, ground displacement, and pressure variations have long-term forces of crack growth in hydrogen-prone materials [9].

2.3. Influence of Operating Conditions and Infrastructure Age

Operating conditions such as pressure, temperature, gas composition, and cycling of loads, among others, have a significant impact on the susceptibility of gas network materials to hydrogen-related degradation. The increased operating pressures raise the hydrogen solubility and flux into the metal, and the pressure cycling related to the demand variability may speed up the fatigue-induced crack propagation in the embrittled materials. Temperature is also a two-sided effect, in that higher temperatures increase the rate of diffusion of hydrogen and can also decrease the trapping efficiency, resulting in the complex and non-linear impacts on the progression of damage [24,30].

These are further compounded by infrastructure age. Older pipelines might also have defects present, like corrosion pits, weld lines, or microcracks that have developed over decades of methane service. These defects can be reactivated by exposure to hydrogen, which reduces the threshold stressing intensity at which crack propagation is possible. Consequently, the parts that have worked safely with a methane-only environment can degenerate faster as soon as the hydrogen is added, although no visible alterations in operating conditions can be noticed [31].

These two factors in combination point to the challenge of establishing universal safe hydrogen blending limits. The response of materials is also contextual in that it not only changes between the segments of a pipeline, but also within the same components, which differ according to local stress states and microstructural characteristics [32].

2.4. Implications for Seals, Joints, and Non-Metallic Components

Although a lot of the literature on hydrogen embrittlement is developed in regard to metallic pipelines, non-metallic components and interfaces are important aspects of overall system integrity. Hydrogen permeation is especially likely to affect elastomeric seals, gaskets, and polymer liners because hydrogen has a small molecular size and is very diffusive. Absorption of hydrogen may cause swelling, blistering, and degradation of mechanical strength in polymers, affecting the sealing performance and making the polymer more vulnerable to leakage [25,33].

Another area of vulnerability is joints and verified joints that have been welded [23,34]. Microstructural heterogeneity and stress remnants in suspect zones of welds usually encourage the trapping of hydrogen and crack propagation. In systems of hydrogen-blended, these local weak points could be preferential points of leakage long before the bulk pipeline material exhibits any evidence of corrosion. The aggregate impact of hydrogen interactions between metallic and non-metallic parts thus complicates the traditional assumptions on which the integrity of a pipeline may be determined on the sole factor of the strength of the pipe walls.

Combined, hydrogen and material interaction patterns in natural gas infrastructure represent a system with an intricate topography of degradation where embrittlement, permeation, and interface failure interrelate and represent a multi-scaling transformation. These mechanisms precondition leakage behavior that is qualitatively different from that in systems only containing methane, and the impact of mechanical failure on the environment is also of interest, as well as the effects of hydrogen-induced integrity loss [35].

3. Embrittlement-Induced Leakage Pathways and Failure Modes

The deterioration of gas infrastructure materials under the influence of hydrogen does not necessarily cause uncontrolled rupture and containment loss. Rather, hydrogen embrittlement tends to occur in the form of non-obvious, progressive over time damage mechanisms that modify the permeability or tightness of the pipeline systems. This change in failure behavior when using hydrogen-blended natural gas networks has significant consequences on the leakage evolution, leakage detection, and exposure to the environment because the embrittlement-induced leakage can occur at a fundamentally different rate and location than in traditional methane service [21,36].

3.1. Transition from Material Degradation to Leakage

Hydrogen embrittlement enhances the propagation and formation of cracks at the stress concentrators of weld toes, corrosion pits, threaded connections, and mechanical joints. Developing and accumulating microcracks will form preferential pathways through which gases will migrate through the pipe wall or interfaces. In contrast to sudden burst failures, such flaws are allowed to be mechanically stable, allowing unbroken or discontinuous leakages of gases. The leakage that follows is usually diffuse, spatially disseminated, and chronic, which is not easily identified through the pressure-based monitoring systems [23,37].

At the microstructural level, hydrogen induced damages are also capable of enhancing effective permeability by modifying grain boundary cohesion and enhancing intergranular transport [38]. Hydrogen can also escape into the surrounding environment even without through-wall cracks when there are thin areas, worn-out coating, or polymeric protective layers. This shift of structural degradation to functional leakage is a very important but frequently neglected stage of pipeline failure development.

3.2. Leakage Characteristics Specific to Hydrogen-Blended Systems

Hydrogen leakage shows characteristics that separate it from methane-dominated leakage even in instances where both gases are released at the same time. The molecular weight and high diffusivity of hydrogen make it move rapidly through microdefects and porous media and escape through defects that would be effectively impermeable to methane. Consequently, hydrogen can be lost more selectively, and the composition of the rest of the gas stream will change to form focal areas with hydrogen-enriched subsurface [39].

This is further complicated by the low volumetric energy density of hydrogen that makes it difficult to evaluate leakage. Small mass fluxes can be associated with high volumetric leakage rates, but yield small amounts of pressure change in the pipeline. Therefore, leakage due to hydrogen embrittlement can be sustained without activating the conventional alarms or functional interventions. This cumulative gas release may, over time, be the result of such chronic leakage as might otherwise be associated with infrequent massive failures, especially in large-scale distribution systems [40].

3.3. Failure Modes in Buried Pipelines and Joints

External loading conditions and soil structure interactions have a strong impact on embrittlement-induced leakage in buried pipeline systems. The other stresses that can be added to the existing stresses are ground settlement, thermal expansion, and vibrations introduced by traffic, which may influence the rate at which cracks propagate in hydrogen-exposed materials. Welded joints and girth welds in particular suffer because they have both metallurgical heterogeneity and other stresses existing in the welded product that have been caused as the welding is being done and the product is in place [23,41].

Another type of failure mode is flanged connections and mechanical joints. **Table 3** classifies embrittlement-sensitive leakage pathways as follows, as per their initial cause, anticipated leak type, and real-world detection constraints that arise in buried infrastructure. Penetration of Hydrogen through gaskets and sealing materials can result in a progressive loss of tightness, especially under cyclic pressure conditions. Leakages in this instance may be experienced without any apparent structural damage, thus blurring the early warning signs further. Such failure modes are distributed, which means that the approach of treating the pipeline integrity by periodically attacking a few critical points is incorrect [42].

Table 3. Embrittlement-induced leakage pathways, expected signatures, and detection challenges.

Leakage Pathway/ Failure Mode	Initiating Condition	Typical Leak Character	Why Hydrogen Blending Increases the Likelihood	Detection Challenge in Practice
Through-wall microcrack in the pipe body	Subcritical crack growth from a pit/defect	Chronic low-rate; may be intermittent	Hydrogen accelerates crack initiation/growth	Minimal pressure signal; diffuse subsurface migration
Weld/HAZ cracking	Residual stress + metallurgical heterogeneity	Localized, persistent, may grow	Trapping and stress concentration in weld regions	Often buried; difficult localization without targeted inspection
Gasket/seal permeation and loss of tightness	Polymer absorption/permeation; cycling	Diffuse, low-rate, interface-driven	Hydrogen diffuses/permeates faster than methane	Odorization may be less informative; weak surface cues
Threaded/mechanical joint leakage	Assembly variability; aging; vibration	Frequent small leaks	Hydrogen preferentially escapes through microgaps	Requires close-range surveys; hard to attribute to embrittlement vs. wear
Coating/interface degradation (indirect)	Aging coatings + defect growth	Spatially spread seepage	Hydrogen can exploit microdefects and interfaces	Gas disperses before reaching surface sensors

3.4. Detectability and Monitoring Challenges

The leakage routes facilitated by hydrogen embrittlement are a major challenge to the current monitoring and detection measures [7,9]. Conventional models are based on pressure drop analysis, odorant detection, or periodic checks, which are also optimized for the behavior of methane. The high diffusiveness and low rate of leakage of hydrogen make these techniques less sensitive, especially in the subsurface, where the gas can diffuse before the detection points.

In addition, hydrogen reaction with soils and groundwater may be able to conceal leakage further [43]. The surface indicators may be attenuated by dissolution, microbial consumption, and dilution, and slow down the process of identification and response. This detectability gap raises the chances that leakage due to embrittlement will go undetected over longer periods, and the potential effects on the environment are more pronounced. Attributing causes once contamination or geochemical anomalies are detected is more complicated.

3.5. Implications for Long-Term Leakage Evolution

In a system-level view, the leakage caused by embrittlement is a transition to discrete failures, which are event-driven to a regime of chronic loss of integrity. During prolonged exposure to hydrogen, defects may increase and develop through forking and branching of leakage pathways, and new defects may form due to the previously developed ones growing or merging. This dynamically changing behavior is a contrast to the more or less stable leakage patterns used in risk evaluation, which are usually based on methane [44].

In the long run of operation, such leakage can greatly produce a change in the gas infrastructure-subsurface environment interaction. The need to identify embrittlement-induced leakage as a particular failure mode is thus critical to formulate the behavior of pipelines in the presence of hydrogen blending realistically and to predict downstream hydrogeology changes, as discussed in the next section [45].

4. Implications for Hydrogeological Integrity

The leakage nature of the hydrogen embrittlement makes the effects of infrastructure deterioration more far-reaching than the engineering reliability to the subsurface environmental protection [16,46]. Hydrogen-blended gas released through leaking buried gas pipelines gets into complex hydrogeological environments in the form of soils and unsaturated zones, fractured media, and groundwater-bearing formations. In these systems, the hydrogen behavior of transportation and reactivity is very different compared to methane, and it brings new concerns about the effects of gas leakage on subsurface integrity in both the short and long term.

4.1. Subsurface Migration and Transport Processes

After being emitted into the subsurface, Hydrogen moves in porous media and fractures due to the combined effects of advection, diffusion, and buoyancy [47]. Its low density and small size facilitate fast diffusion due to its small size through soil pores and along the preferred routes like utility corridors, bedding planes, and fracture networks. Hydrogen is less susceptible to entrapment than methane and can extend over a greater distance than the leakage source before dissipation or reaction, especially in dry or coarse-grained soil.

Hydrogen can be temporarily concentrated in the vadose zone below low-permeability layers or artificial surfaces to form localized areas of high gas concentration. Hydrogen can be laterally or vertically migrating in these zones that may interfere with the shallow aquifer or surface outlets at different locations than the source of leakage. This makes the attribution of a source more challenging and disrupts the traditional beliefs that the effects of gas are spatially limited to the local surroundings of a pipeline infrastructure [48].

4.2. Interactions with Groundwater Systems

Hydrogen, which flows into saturated areas, reacts directly with groundwater where it can dissolve, diffuse, or be taken up by microbial reactions. However, although the hydrogen solubility of water is comparatively low, persistent or chronic leakage may retain dissolved hydrogen levels in aqueous solutions at levels that affect aqueous geochemistry. Specifically, hydrogen is a strong electron donor that can be used in a reductive reaction to change redox conditions in aquifers [49].

A change in redox conditions may result in a trickle-down effect on the quality of groundwater [50]. The process of reduction can activate redox-reactive components like iron, manganese, or arsenic and have an impact on the integrity of already established contaminant pipes. In aquifers that have already been affected by organic contaminants, the availability of hydrogen can be favored towards the degradation pathways in microbes, which can promote the process of natural attenuation, although they also generate intermediate products whose impacts on the environment are unpredictable. These reactions bring out the two-dimensionality of hydrogen in that it is a prospective perturbant and biogeochemical driver in groundwater systems.

4.3. Microbial and Biogeochemical Responses

Hydrogen addition into the underground environment will be capable of promoting hydrogenotrophic microbial communities comprising methanogens, sulfate reducers, and acetogens [13]. **Table 4** provides an overview of hydrogeological compartments, prevailing post-leak processes, and field indicators that may be used to infer the effect of hydrogen (-methane) leakage on the integrity of groundwater. The activation of these populations can modify the processes of microbial competition, which affect the production or consumption of methane and change the carbon cycling of soils and aquifers. Hydrogen-based methanogenesis may result in secondary methane production in certain environments and make it difficult to interpret the origin and flux of gases.

Table 4. Hydrogeological implications of hydrogen (-methane) leakage and recommended monitoring indicators.

Hydrogeological Compartment	Dominant Processes after Leakage	Potential Integrity Concern	Measurable Indicators	Interpretation Caveats
Vadose zone soils	Diffusion, advection, microbial uptake	Gas migration to buildings/utility corridors; altered soil redox	Soil-gas H_2/CH_4; O_2/CO_2 shifts; redox proxies	Rapid microbial consumption can mask H_2 presence
Capillary fringe	Dissolution + reaction hotspot	Local redox perturbation affecting mobilization	Dissolved gases; ORP; Fe(II)/Mn(II)	Strongly heterogeneous; temporally variable
Shallow unconfined aquifer	Dissolution, transport, and biogeochemical transformation	Mobilization of redox-sensitive elements; co-contaminant behavior change	DO depletion; sulfate reduction signals; Fe/Mn; alkalinity	Not all changes are uniquely attributable to H_2
Fractured media pathways	Fast preferential migration	Remote emergence; difficult source attribution	Gas anomalies along fractures; conductivity/ORP anomalies	Plumes may be spatially disconnected from the leak
Mixed H_2–CH_4 plume	Fractionation, coupled microbial dynamics	Dual hazard: safety + hydrogeochemistry	H_2/CH_4 ratio evolution; isotopic tools (where available)	Composition may change with distance due to differential transport

The problem of biogeochemical feedback can also affect the survival of hydrogen itself. Localized redox changes on a long-term basis can be mitigated by rapid redox uptake by microbes that lowers the detectable levels but maintains the local redox change. Consequently, the fact that measurable hydrogen is absent at monitoring places does not automatically mean a smaller effect, especially in areas where the biogeochemical processes are more rapid than the physical transport processes [51].

4.4. Coupled Hydrogen and Methane Leakage

In hydrogen-blended natural gas systems, leakage can seldom be that of only hydrogen. The defects caused by embrittlement generally permit co-release of hydrogen and methane, although fractionation is effected by different diffusivity and solubility. Methane is also necessary to take the slower paths or to exit via more extensive microdefects, as the hydrogen would be allowed to escape at a deeper rate than methane. Upon release from an embrittlement-induced leak, hydrogen and methane do not migrate as a fixed-ratio mixture. Due to hydrogen's ~8-fold higher molecular diffusivity in air and ~3–4-fold higher diffusivity in water-saturated porous media, hydrogen preferentially advances ahead of the methane front, especially through macropores, gravel backfill, and fracture networks. Conversely, methane may be retarded by local capillary trapping or slower dissolution. Consequently, the H_2/CH_4 ratio in soil gas or groundwater decreases systematically with distance from the leak under advection-dominated conditions, but can increase locally where methane is preferentially consumed by methanotrophs [52,53].

Hydrogen and methane co-exist and make the environment even more complex. Methane is a risk when it comes to explosions and climate forcing, and hydrogen alters redox and the activity of bacteria in the subsurface. Detection strategies relying on methane sensors or odorants may completely miss hydrogen-dominated plumes. Surface H_2 measurements, if taken without understanding subsurface pathways, can mis-locate the source or underestimate the leaked volume. For risk assessment, the decoupled transport creates dual hazard footprints: a broader, potentially invisible hydrogen influence zone (redox alteration, microbial stimulation) and a narrower methane accumulation zone (explosion, greenhouse gas emission). Therefore, leak attribution and environmental monitoring must measure both gases and consider transport-reaction models that explicitly include differential migration [54].

4.5. Implications for Regulation and Environmental Risk Assessment

The existing environmental risk models of gas infrastructure rest mostly on experience of the leakage of methane and disastrous failure conditions [40,55]. Long-term low-rate hydrogen release as a form of embrittlement is outside the scope of most of the regulatory limits and monitoring demands, especially when the effects are seen through a prolonged hydrogeochemical transformation other than immediate contamination. Such a regulatory deficiency is particularly worrying in areas that depend on shallow groundwater availability or those that have complicated underground geology.

The evaluation of the hydrogeological integrity under hydrogen blending thus needs a new conceptualization that integrates the material degradation, leakage progression, and the underground reaction [11,17]. Lack of such models, the environmental aspect of hydrogen embrittlement risks would be underestimated, and this may erode the trust of the people and the long-term viability of hydrogen-based decarbonization policies. Such implications are not to be ignored, and this is the reason why it is important to detect and mitigate such implications so as to make energy transition pathways consistent with the protection of the subsurface environment.

5. Conclusions and Future Perspectives

Hydrogen addition to existing natural gas systems is a strategically significant direction towards increasing the energy transition speed, but it also brings on board degradation processes and environmental hazards that are not fully managed by the existing infrastructure design and regulatory paradigm. The present review has explored the hydrogen blending process in the interrelated aspects of material integrity, leakage development, and hydrogeological influence, and embrittlement-related leakage as an important but not well-recognized danger to subsurface environmental systems. **Figure 2** summarizes the integration needs and priority knowledge gaps spanning materials performance, integrity management, leak detection, subsurface transport–reaction modeling, and governance.

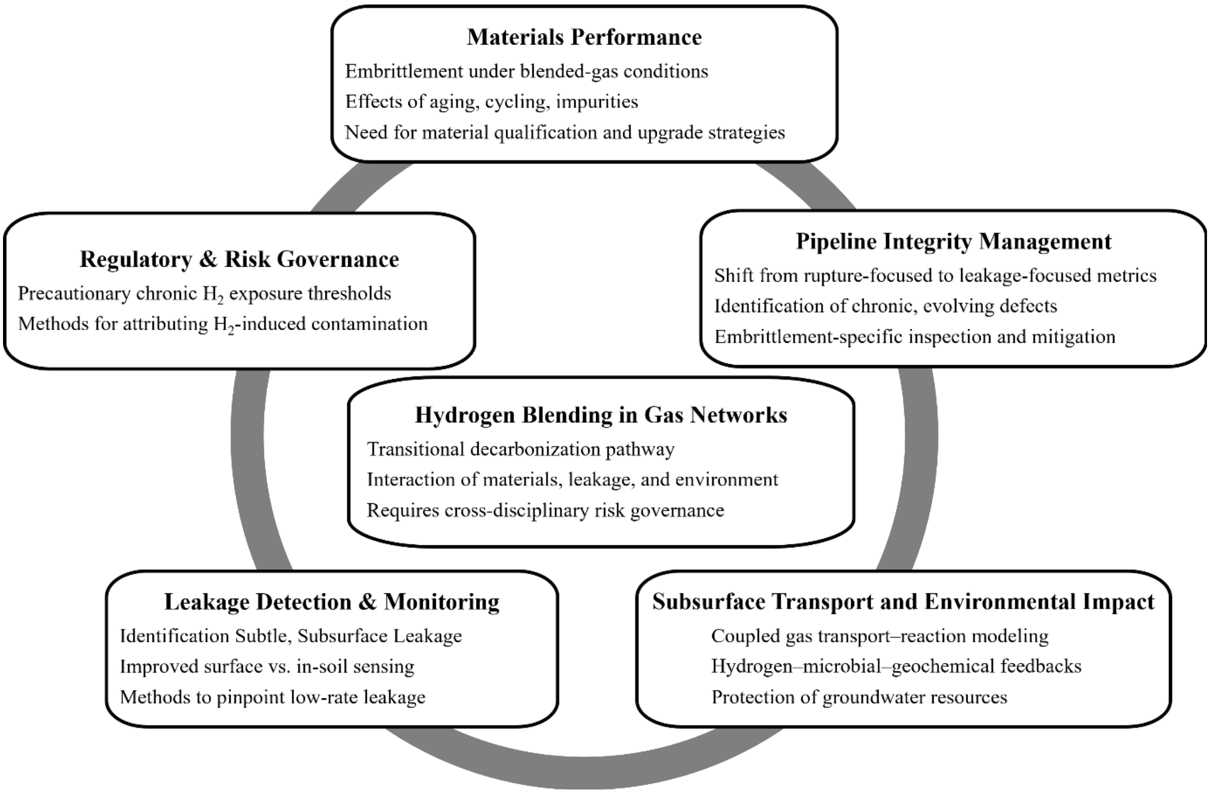

Figure 2. Integrated framework of knowledge gaps and implementation priorities for safe hydrogen blending.

The interactions between hydrogen and materials change the nature of the failure of the old gas infrastructure fundamentally. Instead of causing mainly catastrophic rupture, hydrogen embrittlement facilitates progressive degradation, microcrack formation, and loss of sealing performance through metallic and non-metallic components. These are processes that enable chronic and slow-rate leakages that could possibly go unnoticed during long periods of operation. Since hydrogen diffuses more easily than methane and binds to dislocations much more strongly, even small mixing ratios can be converted into disproportionate leakage risk, both in aging networks that are heterogeneous in terms of material properties and that contain prior damage.

The review also shows that leakages caused by embrittlement have much more far-reaching consequences than the safety and energy efficiency of the pipeline. Hydrogen is very mobile and reactive when emitted into the subsurface, which allows it to move through soils and aquifers and disturb hydrogeological systems. Contact with the groundwater can alter the redox environment, activate the microorganisms, and determine the behavior of naturally occurring elements and anthropogenic contaminants. In the event of a combination of the leakage with the release of methane, the mixed-gas plumes caused further complication, which mixture of climate-relevant emissions and disturbances speckled on the local environment, but is not easily tracked and assigned.

One of the main conclusions of such a synthesis is that hydrogen embrittlement cannot be regarded as only a material or mechanical reliability problem. Rather, it is an interdisciplinary problem that demands the incorporation of materials science, pipeline engineering, subsurface hydrology, and environmental geochemistry. Current systems of integrity management, which are optimally designed around a system of methane and discrete system failures, do not capture the diffuse and dynamic hydrogen-related leakage. Likewise, the environmental risk assessment and regulatory levels fail to cover chronic hydrogen exposure in underground settings, especially where effects are observed over a long period of time, and not as a single instance of acute contamination.

As a prospect, some research and implementation priorities can be identified. There is a need to gain better insight into hydrogen embrittlement during realistic blended gas environments, such as the effect of cyclic loading, material aging, and nonuniformly distributed microstructures. It is also crucial that the leakage detection and monitoring strategies are developed that could detect the low-rate hydrogen release in underground infrastructure and track its migration in complicated geological environments. Hydrogeologically, such coupled transport-reaction complexity as inclusion of microbiological reactions and geochemical feedbacks is fundamental in forecasting long-term effects in the groundwater systems.

Policy and planning perspective. This review indicates that the findings of this review are that hydrogen blending policies need to be considered in the context of a bigger systems approach, which explicitly takes into account protection of the subsurface environment. Establishing the safe blending limits, setting the priorities in terms of the infrastructure areas to be upgraded, and adjusting monitoring demands to the risks unique to hydrogen use will be essential to ensure that people will not lose trust and adhere to regulations. Precautionary measures that prevent the occurrence of leakages caused by embrittlement, in this regard, can eventually be more economical than mitigation measures that occur after the environmental degradation has taken place.

To sum up, hydrogen blending has a great potential in terms of decarbonization as a transitional approach; it should be implemented in the current natural gas networks, and with new integrity and environmental challenges to be explicitly identified. Representing the leakage caused by embrittlement as a risk to hydrogeological integrity, this review highlights the importance of the concerted research and governance strategies that would allow the energy transition to be carried out without disturbing the subsurface environmental systems, on which societies rely.

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