UDK 504.054
MRNTI 87.03.07
DOI 10.56525/WNKA2594

ENVIRONMENTAL RISK ASSESSMENT OF GREEN HYDROGEN TRANSPORTATION AND STORAGE

Ramazan A.*, Taizhanova L., Turkmenbay N.
Yessenov University, Aktau, Kazakhstan
e-mail: akhmet.ramazan@yu.edu.kz, lyailim.taizhanova@yu.edu.kz, nursultan_hse@mail.ru

Abstract. Green hydrogen transportation via pipelines demonstrates substantially lower environmental impact than truck-based delivery, with compressed gas via pipeline achieving 1.57 kgCO2-eq/kgH2 compared to 3.58 kgCO2-eq/kgH2 for liquid organic hydrogen carriers. Pipeline transport achieves 38-85% lower energy footprint than alternative options, with solar electrolysis coupled with pipeline delivery representing the least ecologically intensive pathway. For storage, underground salt caverns at temperatures exceeding 122°C eliminate microbial risks affecting hydrogen recovery and infrastructure integrity, while storage and transport collectively account for approximately 35.5% of total greenhouse gas footprint when hydrogen is liquefied and transported by road. Energy penalties remain substantial across pathways, with liquefaction incurring up to 40% energy losses and compression requiring 15% of hydrogen's lower heating value. Environmental risks extend beyond greenhouse gas emissions to encompass water consumption particularly acute in arid regions, depletion of rare metals and critical materials in electrolyzers, land use impacts, and marine biodiversity loss from offshore platforms. Critical knowledge gaps include incomplete characterization of hydrogen leakage atmospheric effects and insufficient end-of-life equipment management frameworks. Regional variations in policy contexts, infrastructure availability, and site-specific geological conditions fundamentally influence optimal pathway selection, with no single method dominating across all environmental dimensions simultaneously. Current assessment methodologies predominantly employ global warming potential as the primary metric, with expanded indicator frameworks needed to capture water stress, biodiversity impacts, and material circularity for comprehensive environmental risk characterization.

Keywords: Green hydrogen, Life Cycle Assessment, Hydrogen pipeline transport, Environmental risk assessment, hydrogen leakage.

Introduction

The global imperative to mitigate climate change and achieve carbon neutrality by mid-century has positioned green hydrogen (GH2) as a cornerstone of the future energy landscape. Produced through water electrolysis powered by renewable energy, GH2 offers a versatile, carbon-free alternative for decarbonizing hard-to-abate sectors, including heavy industry, long-haul transport, and seasonal energy storage [3]. However, the geographical mismatch between regions with abundant renewable resources and high-demand industrial hubs necessitates the development of robust, efficient, and environmentally safe international hydrogen supply chains [4].

The large-scale deployment of a hydrogen economy is fundamentally constrained by the technical and economic challenges associated with hydrogen's low volumetric energy density and high diffusivity [3]. Consequently, several transportation and storage vectors have emerged as leading candidates for global shipping corridors: high-pressure pipelines, liquid organic hydrogen carriers (LOHC), and ammonia synthesis. While pipelines are well-suited for regional transport and established land routes, intercontinental trade increasingly relies on chemical carriers like ammonia and LOHCs, which can leverage existing maritime infrastructure and offer higher storage densities [2, 4].

Despite their potential, each vector introduces unique environmental risks and lifecycle impacts that must be rigorously assessed to ensure the net-sustainability of the hydrogen value chain. A critical metric in this regard is the Lifecycle Carbon Footprint (LCF), which accounts for emissions across the entire supply chain-from production and conversion (e.g., compression, hydrogenation, or Haber-Bosch synthesis) to transport, storage, and final reconversion [1, 2]. Preliminary studies indicate that the LCF of these vectors is highly sensitive to the carbon intensity of the energy used for processing and the round-trip efficiency of the chemical cycles [1, 4]. For instance, the energy penalties associated with LOHC dehydrogenation or ammonia cracking can significantly inflate the total carbon footprint if not powered by low-carbon sources [2, 3].

Furthermore, the long-term environmental safety of these technologies depends on understanding their chemical degradation pathways and potential ecological impacts during accidental releases or routine operations. High-pressure pipelines are susceptible to hydrogen-induced embrittlement and corrosion, which can lead to leaks and integrity failures [1]. LOHCs, while theoretically reversible, may undergo catalytic or thermal degradation over multiple cycles, producing unknown byproducts and affecting carrier longevity [3]. Ammonia, despite its advantages as a carbon-free fuel and carrier, presents significant toxicity risks to marine ecosystems and human health in the event of spills along shipping corridors [4].

While existing literature has extensively covered the techno-economic aspects of hydrogen transportation, there remains a critical knowledge gap regarding the comparative environmental risk assessment (ERA) of these vectors, particularly concerning their degradation behavior in diverse environments. This article aims to address this gap by providing a comprehensive environmental risk assessment of green hydrogen transportation and storage via high-pressure pipelines, LOHC, and ammonia synthesis. By integrating lifecycle carbon footprint analysis with an evaluation of chemical degradation pathways within the context of global shipping corridors, this study identifies the key trade-offs and environmental safeguards necessary for a sustainable global hydrogen trade.

Materials and methods. In this study, we conducted a systematic search and analysis of scientific literature concerning the environmental risk assessment of green hydrogen transportation and storage. The search query was executed across major academic databases, including Scopus, Web of Science, and Google Scholar, yielding an initial sample of 50 highly relevant publications. During the screening phase, we performed a comprehensive evaluation of the abstracts, selecting papers based on a set of rigorous criteria. Our primary focus was on studies dedicated exclusively to green hydrogen produced via electrolysis using renewable energy sources. An essential condition for inclusion was the detailed examination of supply chain infrastructure: transportation methods (pipeline, road, rail, or maritime transport) and storage technologies, encompassing compressed gas, cryogenic liquids, as well as underground and material-based systems.

We carefully selected articles that provided a direct environmental risk assessment, environmental impact analysis, or life cycle assessment (LCA). It was imperative that the studies reported specific quantitative or qualitative outcomes, such as emission levels, leakage rates, ecosystem impacts, soil and water contamination risks, and climate effects. Particular attention was paid to the academic quality of the sources; thus, our final selection comprised only peer-reviewed articles, systematic reviews, conference proceedings, and reports from reputable organizations. Furthermore, we evaluated the commercial relevance of the research, prioritizing papers that described real-world implementations, pilot projects, demonstration facilities, or validated modeling studies of commercial-scale hydrogen infrastructure.

To systematize the information during the data extraction phase, we employed a large language model, providing it with detailed instructions to retrieve specific parameters from each paper. The extraction process was designed to detail the technical specifications of the assessed transportation and storage methods, alongside their integration with renewable energy systems. We identified the full spectrum of environmental risks, covering not only greenhouse gas emissions and environmental

pollution but also resource depletion, biodiversity impacts, specific atmospheric effects of hydrogen leakage, and waste management issues at the end of the life cycle. Concurrently, data regarding the applied methodologies were extracted: we analyzed system boundaries, utilized metrics (such as carbon footprint or toxicity potential), data sources, and approaches to uncertainty testing.

To construct an objective overview, we also aggregated information on the magnitude of the identified risks, including quantitative impact indicators, hazard levels (Table 1), and confidence intervals. Significant emphasis was placed on mitigation strategies, ranging from the implementation of novel materials and safety protocols to regulatory recommendations and site selection criteria. Finally, we consolidated the results of comparative analyses across various infrastructure solutions, accounted for geographic contexts and local environmental constraints, and highlighted the authors' key findings. This comprehensive approach allowed us not only to systematize the primary environmental challenges associated with the green hydrogen supply chain but also to identify critical gaps in current knowledge, outlining clear trajectories for future research in this domain.

Results

The included studies span diverse methodological approaches and geographic contexts. Seven studies were available as abstracts only, while three provided full text access. The majority employed life cycle assessment frameworks [1–3, 6], with variations including microbial risk assessment [4], safety-focused CFD modeling [10], and technical feasibility reviews [5]. Geographic coverage ranged from specific regional analyses in California [3], the UK continental shelf [4], and Latin America [7] to global assessments [5, 8, 10].

Table 1 - Characteristics of Included Studies

Study	Study Type	Primary Focus	Geographic Context	Assessment Framework
Hanif Tayarani et al., 2022	Comparative LCA [3]	Transportation pathways via pipelines and trucks [3]	California, USA [3]	LCA using GREET model [3]
E. Thaysen et al., 2023	Microbial risk assessment [4]	Underground storage in depleted gas fields [4]	UK continental shelf [4]	Novel microbial growth constraints framework [4]
Chiara Signoria et al., 2023	EHSS management analysis [7]	Production, transportation, storage, and energy carriers [7]	Latin America and Caribbean [7]	IWRM tools, BAT gap analysis [7]
R. Hren et al., 2023	Environmental footprint assessment [2]	Production, storage, and transport pathways [2]	Not specified [2]	LCA framework [2]
Nan Ma et al., 2023	Review of storage technologies [8]	Large scale green hydrogen storage and transportation [8]	Global [8]	Technical and economic evaluation [8]
B. Widera et al., 2020	Comparative technology review [9]	Production, storage, transportation, and applications [9]	Not specified [9]	Comparative analysis of environmental impacts [9]

Study	Study Type	Primary Focus	Geographic Context	Assessment Framework
Malik Sajawal Akhtar et al., 2021	Cradle-to-gate LCA [1]	Seven inland delivery pathways [1]	Not specified [1]	LCA framework [1]
A. Sola et al., 2024	LCA review synthesis [6]	Green hydrogen supply chains [6]	Not specified [6]	LCA synthesis of 35 papers [6]
Zahra Gholami et al., 2025	Comprehensive technology review [5]	Storage and transportation solutions [5]	Global with focus on specific countries [5]	Technical feasibility and energy efficiency analysis [5]
M. Calabrese et al., 2024	Safety and risk assessment review [10]	Hydrogen value chain safety challenges [10]	Global, with European focus [10]	CFD simulations and quantitative risk assessment [10]

Greenhouse Gas Emissions and Climate Impacts

Pipeline transportation consistently demonstrated lower greenhouse gas emissions compared to truck-based delivery. The Hanif Tayarani et al. study found that solar electrolysis through pipelines produced 50.29 g CO2eq per MJ of hydrogen consumed for 1% pipeline attribution [3], representing the least ecologically intensive pathway [3]. In contrast, steam methane reforming with truck transportation yielded the highest GHG emissions [3].

Akhtar et al.'s comparative LCA revealed substantial variation across seven delivery pathways, with compressed gas via pipeline achieving 1.57 kgCO2-eq/kgH2 [1], while liquid organic hydrogen carriers exhibited 3.58 kgCO2-eq/kgH2 [1]. When LOHC systems utilized produced hydrogen for dehydrogenation heating, GWP decreased by approximately 35% to 2.34 kgCO2-eq/kgH2 [1]. Direct ammonia utilization in fuel cell vehicles showed promising results at 1.62 kgCO2-eq/kgH2 [1].

Hren et al. quantified that storage and transport could account for approximately 35.5% of the total GHG footprint in the hydrogen value chain when liquefied and transported via road rather than pipeline [2]. The study identified gaseous hydrogen transported via pipeline as having 38-85% lower energy footprint than alternative options [2].

The environmental advantage of green hydrogen over conventional systems diminishes when grid electricity supplements renewable sources [6]. This dependency on electricity source represents a critical factor in determining net climate benefits [6].

Water Resource Impacts and Contamination Risks

Water consumption emerged as a significant environmental constraint across multiple studies. Truck transportation pathways consumed more water than pipeline alternatives, with this limitation particularly acute in water-stressed regions like California [3].

Desalination for hydrogen production introduces brine discharge concerns, with Signoria et al. identifying gaps in specific regulations for wastewater discharge from green hydrogen facilities. The sustainability of freshwater demand requires assessment through Integrated Water Resource Management tools and forecasting models, with watershed-scale and local-level evaluations recommended [7].

The production of green hydrogen via electrolysis involves substantial water consumption [6], creating potential conflicts with other water uses in water-scarce regions. Seawater utilization presents

an alternative to reduce freshwater demand [7], though this requires desalination infrastructure with its own environmental implications.

Offshore green hydrogen platforms may cause loss of marine biodiversity [6]. Land use and land fragmentation impact cultural ecosystem services, with potential degradation of resources from land use changes affecting ecosystems and communities [7].

Underground hydrogen storage in depleted gas fields poses risks from microbial activity that can affect hydrogen recovery, cause clogging, and induce corrosion. Thaysen et al. developed a risk categorization system based on subsurface temperatures: no microbial risk above 122°C, low risk above 90°C, and high risk below 55°C. This microbial risk directly influences storage integrity [4].

Geochemical reactivity and microbial activity in underground storage systems create additional environmental concerns, with aquifers and depleted reservoirs facing challenges from gas purity degradation [5]. Depletion of rare metals and critical materials in electrolyzers and power generation equipment represents a potential environmental hotspot. The lack of information about end-of-life equipment management exacerbates resource depletion concerns [6]. The production of onboard hydrogen storage tanks is highly energy intensive [3], contributing to resource demands. For underground storage, the limited availability of suitable salt deposits for cavern construction constrains scalability [5].

Hydrogen leaks during delivery along the supply chain create environmental consequences that remain uncertain [6]. Signoria et al. emphasized that hydrogen leakage requires control, with the substance's expansive flammability limits creating safety and environmental hazards. Hydrogen can embrittle steel infrastructure [7], potentially exacerbating leakage risks over time. Calabrese et al. identified hydrogen leakage as a technical barrier requiring robust safety measures [5, 10], with atmospheric dispersion and explosion risks necessitating comprehensive risk assessment [10].

Cryogenic liquid hydrogen storage incurs energy losses up to 40% during liquefaction, while compressed gas storage requires significant compression energy equivalent to 15% of hydrogen's lower heating value. Material-based storage systems impose energy penalties of 20-40% for dehydrogenation [5]. Water electrolysis demonstrated a net positive energy footprint of 60.32 GJ/t H2 [2], indicating more energy consumed than produced when considering the full production chain. These energy penalties significantly affect the overall environmental profile of different hydrogen pathways.

Table 2 - Quantitative Environmental Impact Assessment

Method Category	Transportation/Storage Type	GWP (kgCO2-eq/kgH2)	Energy Footprint	Key Environmental Trade-offs
Pipeline transport	Compressed gas via pipeline [1]	1.57 [1]	38-85% lower than alternatives [2]	Lower emissions but higher infrastructure costs [3]
Truck transport	Compressed gas via tube trailer [1]	Higher than pipeline [3]	Higher energy requirement [3]	More economical but less environmentally friendly [3]
LOHC with natural gas heating	Liquid organic hydrogen carrier [1]	3.58 [1]	Highest among pathways [1]	Flexibility vs. high emissions [1]

Method Category	Transportation/Storage Type	GWP (kgCO2-eq/kgH2)	Energy Footprint	Key Environmental Trade-offs
LOHC with hydrogen heating	Liquid organic hydrogen carrier [1]	2.34 [1]	35% GWP reduction [1]	Improved efficiency by utilizing produced H2 [1]
Ammonia transport	Liquid ammonia [1]	3.14 [1]	Second highest emissions [1]	High energy density but toxicity concerns [5]
Direct ammonia use	NH3 in direct ammonia fuel cell [1]	1.62 [1]	Promising efficiency [1]	Eliminates reconversion but requires new infrastructure [1]
Cryogenic liquid	Liquid hydrogen [5]	Not specified	40% energy loss in liquefaction [5]	Large-scale transport capability vs. high energy penalty [5]
Underground storage	Salt caverns [5]	Not specified	Mature and scalable [5]	Site availability constraints [5]
Material-based	Metal hydrides, LOHCs [5]	Not specified	20-40% dehydrogenation energy [5]	High volumetric density vs. kinetic limitations [5]

As shown in Table 2, quantitative environmental impact assessment demonstrates that Hydrogen transportation via pipeline achieves the lowest GWP of 1.57 kgCO2-eq/kgH2 compared to alternatives such as Ammonia and Liquid organic hydrogen carrier pathways, highlighting significant trade-offs between emissions, energy footprint, and infrastructure requirements.

The comparative analysis reveals pipeline transport of compressed gaseous hydrogen as the most environmentally favorable option when considering greenhouse gas emissions [1, 3], with solar electrolysis as the production method further minimizing impacts. Truck transportation, despite economic advantages, imposes greater ecological burdens through higher emissions and increased water consumption [3].

Among carrier systems, direct ammonia utilization in fuel cells approaches the environmental performance of pipeline compressed gas [1], though toxicity to aquatic organisms dependent on pH conditions presents additional environmental concerns [7]. Liquid organic hydrogen carriers exhibit the highest environmental burdens unless integrated systems utilize produced hydrogen for process heating [1].

Life cycle assessment emerged as the predominant evaluation framework (Table 3), with global warming potential serving as the primary metric across studies [1, 3]. However, Hanif Tayarani et al. noted that the GREET model employed in their analysis focused primarily on GWP with limited consideration of land and water use impacts [3], representing a critical knowledge gap.

Table 3 - Assessment Methodologies and Frameworks

Study	Primary Framework	Key Metrics	System Boundaries	Uncertainty Analysis
Hanif Tayarani et al., 2022	LCA [3]	GWP, NOx, VOC, PM2.5 [3]	Well-to-wheel, production to FCEV use [3]	Pipeline attribution sensitivity analysis [3]
E. Thaysen et al., 2023	Microbial risk framework [4]	Temperature, salinity data [4]	Underground storage in DGF [4]	Not mentioned [4]
Chiara Signoria et al., 2023	IWRM, BAT analysis [7]	Water sustainability, energy efficiency [7]	Watershed to project design phase [7]	Not mentioned [7]
R. Hren et al., 2023	LCA [2]	GHG, energy footprint, acidification, eutrophication, toxicity, eco-cost [2]	Not specified [2]	Sensitivity analysis [2]
Malik Sajawal Akhtar et al., 2021	LCA [1]	GWP in kgCO2-eq/kgH2 [1]	Cradle-to-gate [1]	Not mentioned [1]
A. Sola et al., 2024	LCA synthesis [6]	GHG emissions, water consumption, land use, material depletion [6]	Not specified [6]	Not mentioned [6]
M. Calabrese et al., 2024	CFD simulations, QRA [10]	Not explicitly specified [10]	Hydrogen value chain safety [10]	Empirical modeling uncertainties mentioned [10]

Figure 1 shows the standard Life Cycle Assessment framework, illustrating the iterative interaction between goal and scope definition, life cycle inventory, and environmental impact assessment, with interpretation conducted across all stages. Hren et al. employed a more comprehensive suite of indicators including acidification, eutrophication, human toxicity potential, and eco-cost [2], achieving broader environmental assessment. The eco-cost framework revealed hydrogen from acid gas achieved -41,188 €/t H2 eco-benefit, while biomass gasification incurred 11,259 €/t H2 eco-cost [2]. Sensitivity analyses were conducted for pipeline attribution scenarios [3] and electricity mix variations [2], though many studies lacked explicit uncertainty quantification [1, 4, 6, 7]. The absence of standardized system boundaries across studies complicates direct comparisons and meta-analysis.

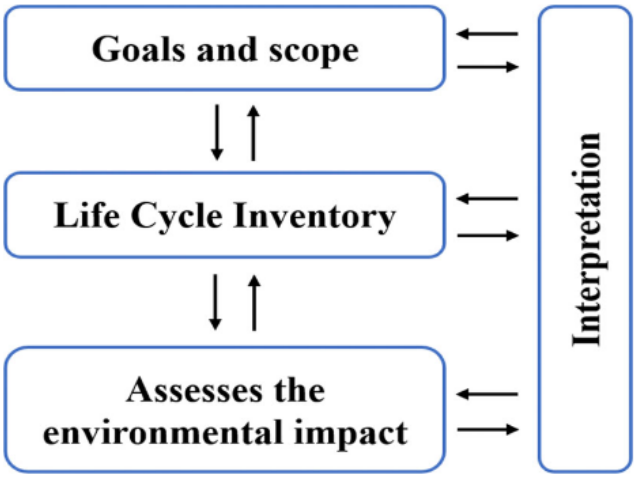


Figure 1. LCA framework based on ISO14040 [16]

Discussion

Geographic and site-specific factors substantially influence environmental risk profiles. In the UK continental shelf, depleted gas fields suitable for hydrogen storage were categorized by microbial risk: 9 fields with no risk (>122°C), 35 low-risk fields (>90°C), and 9 high-risk fields (<55°C). The Southern North Sea emerged as most suitable due to alignment with renewable energy centers and available pipeline infrastructure [4]. California's context highlighted water consumption as a critical constraint, with the Low Carbon Fuel Standards program providing regulatory incentives for carbon intensity reduction. The 400-mile distance from Los Angeles to Sacramento served as a reference case for pipeline vs. truck comparisons [3]. Latin American and Caribbean projects face fragmented regulatory frameworks, with Chile experiencing particular challenges from brine discharge in desalination operations. Water scarcity and rapid project development pace pose challenges for land planning and environmental management [7].

Global variations in green hydrogen production costs reflect policy differences and infrastructure readiness. Australia, the USA, and Morocco are positioned for large-scale production due to renewable energy potential, while Japan, India, and China face greater reliance on imports due to domestic resource or infrastructure limitations. European Union member states show varying levelized costs influenced by policy frameworks and trade dynamics [5].

Underground storage feasibility depends heavily on favorable geological conditions, with limited availability of suitable salt deposits constraining certain regions. Seasonal electricity price fluctuations affect economic viability [5], indirectly influencing environmental performance through operational decisions.

The comparison covers all life cycle stages in Figure 2 defined in the system boundaries, including production, conditioning, storage, transport, and deconditioning. A reference scenario is also included, representing locally produced hydrogen via SMR, without any transportation involved. Results are expressed as relative values, normalized to the highest-impact scenario within each impact category, with the corresponding absolute value indicated. The impact categories considered are Global Warming, Stratospheric Ozone Depletion, Terrestrial Acidification, Freshwater Eutrophication, Human Carcinogenic Toxicity, and Fossil Resource Scarcity.

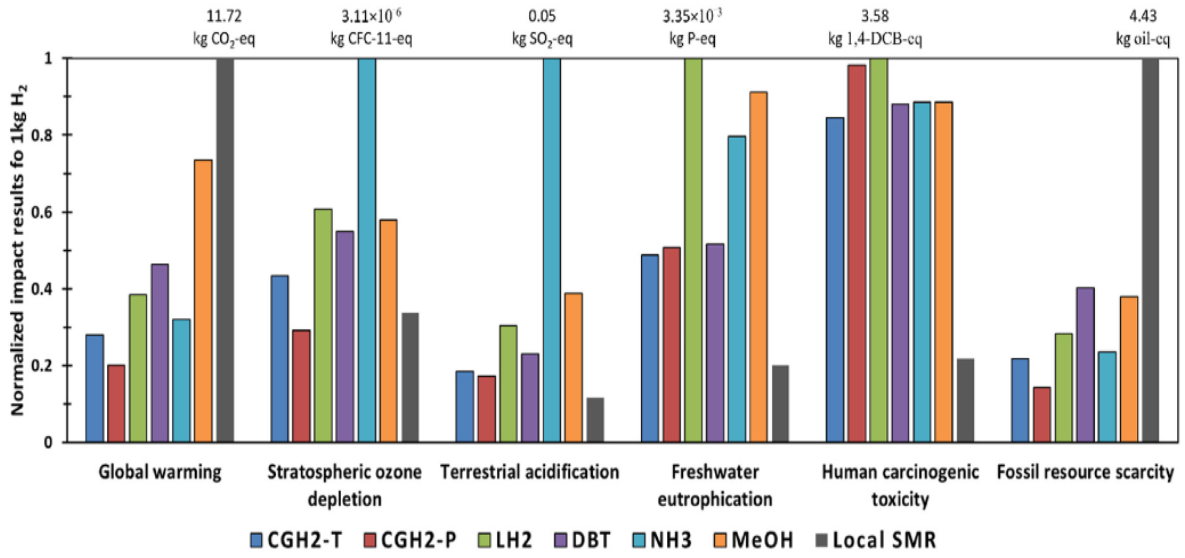


Figure 2. Environmental impact comparison of six green H2 delivery scenarios of 1 kg of H2 [15]

In arid and water stressed regions, auxiliary cooling systems associated with hydrogen production, storage, and compression infrastructure may themselves become a significant source of electricity demand and indirect greenhouse gas emissions. Recent studies from the Aral Sea region demonstrated that solar powered non pump evaporative cooling systems based on saline water can provide an energy efficient and environmentally safer alternative to conventional HVAC technologies in hot and dry climates. The proposed capillary driven system operates autonomously using small photovoltaic panels and saline water, eliminating the need for energy intensive refrigeration cycles and harmful refrigerants such as freon. Such approaches may be particularly relevant for green hydrogen hubs located in desert and coastal regions where freshwater scarcity, weak grid infrastructure, and extreme temperatures increase operational and environmental risks. In addition, the utilization of saline water instead of freshwater supports water conservation strategies critical for sustainable hydrogen infrastructure deployment in arid ecosystems [19].

Environmental Risk Mitigation Strategies

Solar electrolysis integrated with pipeline transportation represents the recommended pathway for minimizing ecological impacts. Innovation in onboard hydrogen tank production technologies offers potential for reducing energy intensity [3]. For liquid organic hydrogen carrier systems, utilizing produced hydrogen for process heating rather than external natural gas reduces GWP by 35% [1].

Underground storage in salt caverns provides mature, scalable options, while cryo-compressed hydrogen technologies balance density advantages with boil-off rate minimization. Advanced materials and green-synthesized nanoparticles for photocatalysis show promise for improving production efficiency [5].

Steel or composite tanks and underground geological formations offer diverse storage options suited to different scales and timeframes. Compressed hydrogen serves short distances and low volumes effectively, while liquid hydrogen at -253°C enables longer-distance transport [7].

Operational Practices and Safety Protocols

Strict compliance with international regulations including ILO convention no.174, EU Directive 2012/18/EU, and UN Recommendations on the Transport of Dangerous Goods forms the foundation of environmental risk management. Development of Safety Management Systems incorporating

quantitative risk assessment and best available technology gap analysis enables systematic hazard control [7].

Pipeline transportation requires sensitivity analysis and attribution optimization [3], while vehicle and infrastructure maintenance demand strict procedural adherence [7]. Regular inspections and worker training mitigate operational risks [10]. CFD simulations support safety measure design and risk assessment [10].

Site Selection Criteria

For underground storage, temperature thresholds provide clear selection guidance: sites above 122°C eliminate microbial risk entirely, while temperatures above 90°C maintain low-risk status. High-risk sites below 55°C should be avoided [4].

Integration with renewable energy production centers optimizes environmental performance [4], with existing pipeline infrastructure offering opportunities for repurposing [4]. Suitable site identification must include buffer zone design [7], with application, scale, and regional infrastructure determining optimal storage method selection [5].

Policy and Regulatory Frameworks

California's Low Carbon Fuel Standards program exemplifies regulatory mechanisms rewarding suppliers for carbon intensity reduction [3]. Establishing stable legal frameworks, providing subsidies, and investing in infrastructure enable market development [5]. European safety standards and codes set benchmarks for international adoption [10].

Integration of safety protocols into national regulations, coupled with state-of-the-art water and energy management measures, forms comprehensive policy approaches [7]. Sustained research investment and government support prove essential for advancing production and storage technologies [5]. Collaborative efforts among researchers, industry, and policymakers represent best practices for reducing environmental impacts [5], with holistic environmental assessment frameworks addressing cumulative impacts across the value chain [7].

The substantial heterogeneity in environmental performance across hydrogen transportation and storage methods reflects distinct operational contexts rather than conflicting findings. Pipeline-based compressed gas transport consistently outperforms alternatives in greenhouse gas intensity [1, 3], but this advantage manifests primarily in contexts with sufficient transport volumes and established infrastructure [3]. The 400-mile California reference case demonstrates pipeline superiority [3], while short-distance, low-volume applications may favor truck-based compressed hydrogen despite higher per-unit emissions [7].

Energy carrier selection involves fundamental trade-offs between energy density, conversion efficiency, and environmental impact. Ammonia achieves high energy density facilitating long-distance maritime transport [5], yet imposes environmental burdens through synthesis energy requirements (3.14 kgCO2-eq/kgH2) [1] and aquatic toxicity risks [7]. Direct ammonia utilization in fuel cells circumvents reconversion penalties, achieving environmental performance approaching pipeline compressed gas (1.62 kgCO2-eq/kgH2) [1]. This suggests that the environmental viability of ammonia as a carrier depends critically on end-use application-direct utilization shows promise, while hydrogen extraction from ammonia introduces substantial environmental penalties.

Liquid organic hydrogen carriers exhibit the highest baseline environmental impact (3.58 kgCO2-eq/kgH2) [1], yet process integration reduces this burden by 35% to 2.34 kgCO2-eq/kgH2 [1]. This sensitivity to system design indicates that LOHC environmental performance depends on thermal management strategies. Studies reporting high LOHC impacts employed external natural gas heating [1], while those with hydrogen self-heating achieved moderate performance [1]. Neither scenario approaches pipeline compressed gas efficiency, suggesting LOHCs remain environmentally disadvantageous even with optimization.

Underground storage environmental risks vary systematically with geological context rather than representing contradictory findings. The temperature-based microbial risk framework reconciles

apparent discrepancies-high-risk classifications below 55°C reflect metabolically active subsurface microorganisms capable of hydrogen consumption, clogging, and corrosion [4], while no-risk designations above 122°C indicate temperatures exceeding microbial tolerance limits [4]. Salt caverns in the Southern North Sea offer favorable conditions [4], whereas aquifers and depleted reservoirs face gas purity challenges from microbial activity [5]. This suggests underground storage suitability depends on selecting sites with appropriate thermal regimes rather than underground storage being inherently high- or low-risk.

The finding that green hydrogen increases global warming potential when grid electricity supplements renewables [6] initially appears contradictory to green hydrogen's low-emission profile. This reflects temporal and geographic mismatches between renewable generation and hydrogen demand rather than a fundamental flaw in green hydrogen technology. Grid electricity in many regions remains fossil-intensive, such that backup power negates production-phase emission advantages. This implies green hydrogen's environmental benefits materialize fully only with dedicated renewable capacity or grid systems achieving high renewable penetration.

Water consumption variations across studies reflect regional availability rather than technology differences. California studies emphasize water constraints [3, 3], while this receives less attention in analyses from water-abundant regions. The recommendation for seawater utilization in coastal Latin American projects [7] demonstrates context-dependent water management strategies. These findings are compatible-water consumption represents a critical constraint in arid regions while remaining manageable in others.

Critical material depletion concerns arise from electrolyzer and renewable energy equipment rather than hydrogen storage and transport infrastructure per se [6]. The lack of end-of-life management information [6] suggests this environmental risk remains poorly characterized rather than absent. Future environmental assessments must incorporate circular economy principles for equipment lifecycles to accurately characterize net environmental benefits.

Energy penalties during liquefaction (up to 40%) [5], compression (15% of LHV) [5], and material-based dehydrogenation (20-40%) [5] represent inherent thermodynamic constraints rather than technological inefficiencies subject to elimination. These penalties establish fundamental efficiency ceilings for different approaches, indicating that method selection must balance energy losses against operational requirements. Compressed gas suits short-term, high-turnover applications despite compression penalties, while liquid hydrogen enables long-distance transport justifying liquefaction energy costs for specific use cases.

The comparative advantage of pipeline transport over road transport increases with distance and volume, with pipelines achieving 38-85% lower energy footprint [2]. This percentage range reflects study-specific assumptions about distance, utilization rates, and comparison baselines. The broad range indicates sensitivity to operational parameters rather than measurement uncertainty, suggesting pipeline advantages amplify at higher capacity utilization factors.

Studies emphasizing greenhouse gas metrics favor pipeline compressed gas [1, 3], while those incorporating broader environmental indicators including water consumption [3], land use, and material depletion [6] reveal more complex trade-offs. This methodological variation explains apparent inconsistencies in environmental rankings-no single method dominates across all environmental dimensions simultaneously. Comprehensive environmental assessments require multi-criteria frameworks encompassing climate, water, land, materials, and ecosystem impacts rather than relying solely on carbon footprint metrics. The California policy context demonstrates that regulatory frameworks incorporating Low Carbon Fuel Standards can drive adoption of lower-emission pathways like solar electrolysis with pipeline transport [3]. European safety standards provide parallel regulatory drivers [10]. However, Latin America's fragmented regulatory framework [7] indicates policy harmonization remains incomplete globally. This suggests environmental performance improvements require not only technological optimization but also supportive policy ecosystems. Geographic

distribution of suitable storage sites-concentrated in specific geological formations like salt caverns in the Southern North Sea or regions with favorable thermal regimes creates spatial mismatches with hydrogen demand centers. This necessitates long-distance transport infrastructure, reintroducing environmental impacts that underground storage alone would minimize. Optimal system configurations must therefore consider entire supply chain geography rather than optimizing individual components in isolation. The finding that hydrogen from acid gas achieves the highest eco-benefit (-41,188 €/t H2) while biomass gasification incurs the highest eco-cost (11,259 €/t H_2) [2] reflects byproduct utilization benefits versus resource-intensive production. This suggests waste stream valorization offers environmental advantages over dedicated biomass processing, though acid gas availability remains geographically constrained to specific industrial facilities.

Environmental risk assessment methodologies show limited standardization, with most studies employing LCA frameworks [1–3, 6] but varying substantially in system boundaries, impact categories, and uncertainty treatment. The GREET model's focus on global warming potential with limited consideration of land and water impacts [3] exemplifies how methodological choices shape conclusions. Comprehensive risk characterization requires expanding beyond climate metrics to encompass water stress [7], biodiversity impacts, and material circularity [6].

Studies identifying hydrogen leakage as a concern with uncertain environmental consequences [6] reflect knowledge gaps in atmospheric chemistry rather than contradicting findings of low leakage rates from properly maintained systems [7]. Hydrogen's indirect climate forcing through hydroxyl radical reactions and stratospheric water vapor formation requires further research to fully characterize environmental impacts [6]. Current assessments likely underestimate atmospheric effects due to incomplete mechanistic understanding.

The variation in reported greenhouse gas intensities-from 1.57 kgCO2-eq/kgH2 for pipeline compressed gas [1] to 3.58 kgCO2-eq/kgH2 for LOHC [1] -exceeds typical LCA uncertainty ranges, indicating real technological differences rather than methodological artifacts. Method rankings remain consistent across studies despite numerical variations, providing confidence in qualitative conclusions even where quantitative precision remains limited. Site-specific microbial risk assessment for underground storage [4] complements rather than conflicts with generalized environmental footprint analyses [1, 2, 6]. Microbial activity represents a local environmental risk requiring site selection criteria [4], while LCA captures regional and global impacts through greenhouse gas accounting. Comprehensive assessment frameworks must integrate multiple spatial and temporal scales to address the full spectrum of environmental risks. The energy footprint of water electrolysis showing net positive values (60.32 GJ/t H2) [2] appears contradictory to hydrogen's role as an energy carrier until recognizing that this represents primary energy input rather than final energy content. The metric reflects conversion efficiency losses inherent in electrolysis, highlighting that green hydrogen serves as an energy vector enabling renewable integration rather than a primary energy source. This fundamental characteristic means hydrogen's environmental benefits depend entirely on the carbon intensity of electricity inputs. Infrastructure repurposing opportunities-utilizing existing natural gas pipelines for hydrogen transport [4, 8] -offer environmental benefits through avoided new construction impacts, yet face technical constraints from hydrogen embrittlement [7] and compositional compatibility requirements. The environmental trade-off between utilizing existing infrastructure with modification costs versus constructing purpose-built hydrogen systems requires case-by-case evaluation considering pipeline age, material composition, and required safety factors.

Conclusions. Pipeline transportation of compressed hydrogen and underground storage in high-temperature geological formations present the lowest environmental risks across greenhouse gas emissions and energy consumption. Green hydrogen transportation and storage environmental risks vary systematically across technological pathways, with pipeline-based compressed gas transport demonstrating the lowest greenhouse gas intensity (1.57 kgCO2-eq/kgH2) when coupled with renewable electrolysis. However, environmental risk profiles extend beyond climate impacts to encompass water

consumption, land use, critical material depletion, and ecosystem effects. Storage and transport contribute approximately 35.5% of total value chain greenhouse gas footprint for liquefied hydrogen via road transport, while pipeline gaseous hydrogen achieves 38-85% lower energy footprint. Underground storage in thermally suitable geological formations (>122°C for salt caverns) provides mature, scalable options with minimal microbial risks, though geographic availability constraints limit universal applicability. Critical knowledge gaps include incomplete characterization of hydrogen leakage atmospheric effects, limited end-of-life equipment management frameworks, and insufficient integration of water stress and biodiversity impacts in standard LCA methodologies. Assessment frameworks predominantly employ global warming potential as the primary metric, with expanded indicator sets needed for comprehensive environmental risk characterization. Regional policy contexts substantially influence environmental outcomes, with California's Low Carbon Fuel Standards, European safety frameworks, and infrastructure availability creating geographic heterogeneity in optimal pathway selection. Site-specific factors including geology, water availability, and renewable energy integration potential determine technology suitability rather than universal rankings applying across contexts.

Future research priorities include standardizing system boundaries and impact categories across LCA studies, quantifying hydrogen atmospheric chemistry effects, developing circular economy frameworks for equipment lifecycles, and integrating multi-scale risk assessment methodologies encompassing local and global environmental impacts. Sustained investment in material science, supportive regulatory frameworks, and collaborative stakeholder engagement prove essential for advancing environmentally optimized green hydrogen systems supporting decarbonization objectives.

REFERENCES

1. Malik Sajawal Akhtar, R. Dickson, J. J. Liu (2021) Life Cycle Assessment of Inland Green Hydrogen Supply Chain Networks with Current Challenges and Future Prospects. ACS Sustainable Chemistry and Engineering. Volume 50, pp. 1-22, https://doi.org/10.1021/acssuschemeng.1c06769

2. R. Hren, Annamaria Vujanović, Yee Van Fan, et al (2023) Hydrogen production, storage and transport for renewable energy and chemicals: An environmental footprint assessment. Renewable & Sustainable Energy Reviews. Volume 173, pp. 1-18, https://doi.org/10.1016/j.rser.2022.113113

3. Hanif Tayarani, Aditya Ramji (2022) Life Cycle Assessment of Hydrogen Transportation Pathways via Pipelines and Truck Trailers: Implications as a Low Carbon Fuel. Sustainability. Volume 14, pp. 1-24, https://doi.org/10.3390/su141912510

4. E. Thaysen, T. Armitage, Lubica Slabon, et al (2023) Microbial risk assessment for underground hydrogen storage in porous rocks. Fuel. Volume 352, pp.1-12, https://doi.org/10.1016/j.fuel.2023.128852

5. Zahra Gholami, Fatemeh Gholami, J. Šimek, Mohammadtaghi Vakili (2025) Advancing hydrogen infrastructure: a review of storage and transportation solutions for a sustainable future. Reviews in chemical engineering. Volume 41, pp.1-15, https://doi.org/10.1515/revce-2025-0024

6. A. Sola, Roberto Rosa, Anna Maria Ferrari (2024) Green Hydrogen and Its Supply Chain. A Critical Assessment of the Environmental Impacts. Advanced Sustainable Systems. Volume 9, pp.1-26 https://doi.org/10.1002/adsu.202400708

7. Chiara Signoria, M. Barlettani (2023) Environmental, Health, Safety, and Social Management of Green Hydrogen in Latin America and the Caribbean. https://doi.org/10.18235/0004888

8. Nan Ma, Weihua Zhao, Wenzhong Wang, et al (2023) Large scale of green hydrogen storage: Opportunities and challenges. International journal of hydrogen energy. Volume 50 https://doi.org/10.1016/j.ijhydene.2023.09.021

9. B. Widera (2020) Renewable hydrogen implementations for combined energy storage, transportation and stationary applications. Volume 16, pp.1-8,https://doi.org/10.1016/j.tsep.2019.100460

10. M. Calabrese, M. Portarapillo, Alessandra Di Nardo, et al (2024) Hydrogen Safety Challenges: A Comprehensive Review on Production, Storage, Transport, Utilization, and CFD-Based Consequence and Risk Assessment. Energies. Volume 17, pp. 20-26, https://doi.org/10.3390/en17061350

11. Salma Serghini, Emmanue Mignard, St́ephanie Muller, et al (2026) International Journal of Hydrogen Energy. Volume 206, pp.1-15, https://doi.org/10.1016/j.ijhydene.2025.153243

12. Senthil Kumar Srinivasan, Srinivas Jayaraman, Bharani Kumar Sekar, et al (2026) Integrated monitoring and lifecycle assessment of green hydrogen, ammonia, and synthetic fuels: Advancing environmental sustainability and carbon traceability. Volume 1 .pp.1-18, https://doi.org/10.1002/ep.70328

13. Mohammed El-Adawy, Ibrahim B. Dalha, Mhadi A. Ismael, et al (2024) *Energy & Fuels,* Review of sustainable hydrogen energy processes: Production, storage, transportation, and color-coded classifications. Volume 38, https://doi.org/10.1021/acs.energyfuels.4c04317

14. Chul-Jin Lee, Ali Cherif, Ha-Jun Yoon (2022) *Renewable and Sustainable Energy Reviews.* Large-scale overseas transportation of hydrogen: Comparative techno-economic and environmental investigation. Volume 165, https://doi.org/10.1016/j.rser.2022.112556

15.Salma Serghini, Emmanuel Mignard, Stéphanie Muller , et al (2026). *International Journal of Hydrogen Energy.* Beyond green hydrogen production: Ground transport within Europe, the hidden environmental impacts, Volume 206, pp.1-15, https://doi.org/10.1016/j.ijhydene.2025.153243

16. Ahmed I. Osman, Mahmoud Nasr, A. R. Mohamed, et al (2024). *WIREs Energy and Environment.* Life cycle assessment of hydrogen production,storage, and utilization toward sustainability. Volume 13, pp. 1-35., https://doi.org/10.1002/wene.526

17. Yessenov University. (2025). Research report on green hydrogen storage, transportation, and monitoring in the Caspian Sea [Research report].

18. Petrosyants Tatyana Valerievna (2024). Yessenov Science Journal. Sustainable Development of Kazakhstan: The Role Of The Green Economy Volume 48, pp. 217-224

19. Uzakov, B. A., & Esemuratova, Sh. M. (2025). Technology of non-pump evaporation cooling based on saline water, operating on solar energy in a dry and hot climate. Yessenov Science Journal, 53(4), 342-348. https://doi.org/10.56525/NAEB4254

ЖАСЫЛ СУТЕКТІ ТАСЫМАЛДАУҒА ЖӘНЕ САҚТАУҒА БАЙЛАНЫСТЫ ЭКОЛОГИЯЛЫҚ ҚАУІПТЕРДІ ЗЕРТТЕУ

***Рамазан А. Қ., Тайжанова Л.С., Туркменбай Н.**
Есенов университеті, Актау, Қазақстан
email: akhmet.ramazan@yu.edu.kz, lyailim.taizhanova@yu.edu.kz, nursultan_hse@mail.ru

Аңдатпа. Сутекті құбырлар арқылы экологиялық таза тасымалдау жүк көлігімен тасымалдауға қарағанда қоршаған ортаға айтарлықтай төмен әсер етеді, құбыр арқылы сығылған газ сұйық органикалық сутегі тасымалдаушылары үшін 3,58 кгco2-экв/кг2-мен салыстырғанда 1,57 кгco2-экв/кг2-ге жетеді. Құбырларды тасымалдау баламалы энергия көздеріне қарағанда 38-85% - ға аз энергия шығынын қамтамасыз етеді, ал күн электролизі құбырларды жеткізумен бірге экологиялық тұрғыдан ең аз қарқынды жолды білдіреді. Сақтау үшін 122°c-тан жоғары температурадағы жер асты тұзды үңгірлері сутекті қалпына келтіруге және инфрақұрылымның тұтастығына әсер ететін микробтық қауіптерді жояды, ал сақтау және тасымалдау сутекті сұйылту және автомобиль көлігімен тасымалдау кезінде парниктік газдардың жалпы көлемінің шамамен 35,5% құрайды. Барлық жолдарда энергия шығындары айтарлықтай болып қала береді,

сұйылту кезінде энергия шығыны 40% - ға дейін, ал сығымдау кезінде сутектің қыздыру құнының 15% - ы төмен болады. Экологиялық тәуекелдер парниктік газдар шығарындыларынан асып түседі, әсіресе құрғақ аймақтарда суды тұтынуды, электролизерлерде сирек металдар мен маңызды материалдардың сарқылуын, жерді пайдаланудың салдарын және теңіз платформаларында теңіз биоәртүрлілігінің жоғалуын қамтиды. Білімдегі маңызды олқылықтарға сутегінің ағып кетуінің атмосфералық әсерінің толық емес сипаттамасы және жабдықтың қызмет ету мерзімін басқарудың жеткіліксіз жүйесі жатады. Саясат контекстіндегі аймақтық айырмашылықтар, инфрақұрылымның қолжетімділігі және белгілі бір аумақтағы геологиялық жағдайлар жолдарды оңтайлы таңдауға түбегейлі әсер етеді, өйткені қоршаған ортаның барлық өлшемдерінде бір уақытта бірде-бір әдіс басым болмайды. Ағымдағы бағалау әдістемелері негізінен негізгі көрсеткіш ретінде жаһандық жылыну әлеуетін пайдаланады, судың кернеуін, биоәртүрліліктің әсерін және қоршаған ортаға қауіп-қатерді жан-жақты сипаттау үшін материалдық айналымдылықты анықтау үшін кеңейтілген көрсеткіштер жүйесі қажет.

Түйін сөздер: Жасыл сутек, Өмірлік Циклды Бағалау, Сутекті құбыр арқылы тасымалдау, Экологиялық тәуекелді бағалау, Сутектің сыртқа шығуы.

ОЦЕНКА ЭКОЛОГИЧЕСКИХ РИСКОВ ПРИ ТРАНСПОРТИРОВКЕ И ХРАНЕНИИ «ЗЕЛЕНОГО» ВОДОРОДА

***Рамазан А. Қ., Тайжанова Л.С., Туркменбай Н.**
Университет Есенова, Актау, Казакстан
email: akhmet.ramazan@yu.edu.kz, lyailim.taizhanova@yu.edu.kz, nursultan_hse@mail.ru

Аннотация. Транспортировка «зеленого» водорода по трубопроводам оказывает значительно меньшее воздействие на окружающую среду, чем его доставка на грузовиках. При транспортировке сжатого газа по трубопроводу выбросы CO2 составляют 1,57 кг/кг H2, в то время как при использовании жидких органических носителей водорода этот показатель равен 3,58 кг/кг H2. При транспортировке по трубопроводу энергопотребление на 38–85 % ниже, чем при использовании альтернативных вариантов. Наименее энергозатратным способом является электролиз с использованием солнечной энергии в сочетании с транспортировкой по трубопроводу. Для хранения водорода используются подземные соляные пещеры, где температура превышает 122 °C, что исключает риск микробного заражения, влияющего на извлечение водорода и целостность инфраструктуры. При сжижении водорода и его транспортировке по дорогам на хранение и транспортировку приходится около 35,5 % общего объема выбросов парниковых газов. При любом способе транспортировки потери энергии значительны: при сжижении водорода потери энергии составляют до 40 %, а при сжатии — до 15 % от его низшей теплотворной способности. Экологические риски связаны не только с выбросами парниковых газов, но и с потреблением воды, что особенно актуально для засушливых регионов, истощением запасов редких металлов и критически важных материалов в электролизерах, воздействием на землепользование и утратой морского биоразнообразия из-за морских платформ. К критическим пробелам в знаниях относятся недостаточная изученность влияния утечек водорода на атмосферу и отсутствие систем утилизации отслужившего свой срок оборудования. Оптимальный выбор способа транспортировки зависит от региональных особенностей политики, доступности инфраструктуры и геологических условий конкретного участка. При этом ни один из способов не является оптимальным во всех экологических аспектах одновременно. В существующих методологиях оценки в качестве основного показателя используется потенциал глобального потепления, а для комплексной оценки экологических рисков необходимы

расширенные системы показателей, учитывающие дефицит воды, воздействие на биоразнообразие и циркуляцию материалов.

Ключевые слова: Зеленый водород, оценка жизненного цикла, транспортировка водорода по трубопроводам, оценка экологических рисков, утечка водорода.