A Survey on Urban PE Gas Pipeline Safety and Hydrogen-Blended Natural Gas Transportation

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Abstract

This survey paper explores the critical importance of safety and integrity in urban polyethylene (PE) gas pipelines and hydrogen-blended natural gas transportation systems. The integration of hydrogen into existing natural gas networks presents unique challenges, such as material degradation and leakage risks, necessitating advanced safety protocols. A Python-based safety scoring system is highlighted as a robust framework for assessing pipeline integrity and safety risks, thereby enhancing the reliability of gas distribution networks. The paper systematically addresses technical and safety challenges, including hydrogen-induced material degradation and leakage risks, while emphasizing the economic viability of hydrogen blending in natural gas systems. Case studies and demonstration projects underscore the practical implementation of hydrogen blending technologies, providing empirical evidence of their feasibility and effectiveness. The survey advocates for future research to focus on optimizing blending technologies, developing standards for hydrogen blending, and enhancing safety regulations. Additionally, it emphasizes the need for advanced non-destructive testing technologies and strategic policy frameworks to support the transition to sustainable energy solutions. Overall, this survey provides a comprehensive framework for evaluating and ensuring the safety and integrity of hydrogen-blended natural gas pipelines, contributing to the broader goal of reducing carbon emissions and transitioning to a more sustainable energy system.

1 Introduction

1.1 Significance of Safety and Integrity

The maintenance of safety and integrity in urban polyethylene (PE) gas pipelines and hydrogen-blended natural gas systems is crucial due to the unique challenges and hazards these infrastructures present. The incorporation of hydrogen into natural gas pipelines introduces significant safety concerns, primarily related to hydrogen's flammability and explosion risks, alongside the complexities of its handling and storage [1]. This necessitates tailored integrity management approaches, as variations in pipe location and class across pipeline segments require specific solutions [2].

The challenges associated with the mixed transportation of hydrogen in natural gas pipelines are multifaceted, encompassing issues of material degradation, leakage risks, and the overall reliability of the gas distribution network [3]. The aging of PE pipelines, commonly used in urban settings, exacerbates these challenges, impacting performance and safety over time [4]. Frequent incidents in underground pipeline systems, particularly in Chinese cities, underscore the persistent threats to public safety and urban operations [5].

Additionally, blending hydrogen with natural gas raises concerns about safety, efficiency, and economic viability [6]. The unreliability of gas systems poses significant environmental and public safety threats, as well as potential interruptions in gas supply [7]. Addressing these issues necessitates

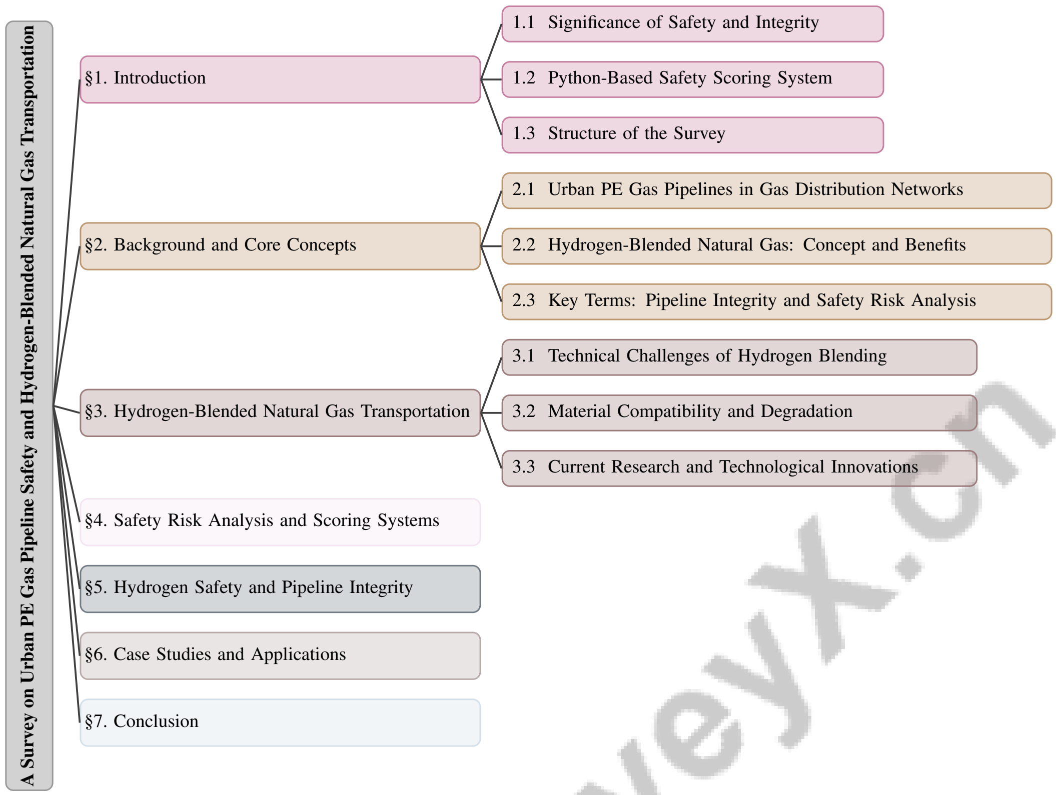

Figure 1: chapter structure

innovative approaches to enhance threat detection and classification in pipeline integrity assessments [8].

Understanding and addressing these safety and integrity challenges is vital for repurposing existing infrastructure for large-scale hydrogen transport. This is essential for enhancing the resilience and reliability of urban gas distribution networks and achieving ambitious environmental targets, such as substantial carbon emission reductions and a transition to sustainable energy systems. Improved assessment methods for gas pipeline functionality, including statistical analyses of failure occurrences and the development of integrity detection technologies, are crucial for identifying vulnerabilities and optimizing modernization strategies. Furthermore, adapting existing natural gas infrastructure for hydrogen distribution is key to achieving net-zero emissions goals, as evidenced by ongoing research in regions such as the Australian Capital Territory and Germany, which explore the economic and technical feasibility of repurposing gas pipelines for hydrogen transport [4, 9, 7, 10].

1.2 Python-Based Safety Scoring System

The implementation of a Python-based safety scoring system within gas pipeline networks represents a significant advancement in risk analysis methodologies, providing a comprehensive framework for assessing pipeline integrity and associated safety risks. This system employs sophisticated computational techniques to evaluate the structural dynamics of hydrogen blending systems, incorporating hydrogen concentration measurement methodologies and operational insights from existing demonstration projects [11]. Through numerical simulations, the system models leakage patterns of hydrogen-blended natural gas (HBNG) and develops effective ventilation strategies to mitigate risks in utility tunnels [12].

Central to this framework is the Pipeline Integrity Management System (PIMS), which systematically evaluates and manages risks across gas pipelines [2]. PIMS enhances pipeline integrity by continuously monitoring and assessing potential threats, thereby improving the reliability and safety of gas distribution networks. The system also integrates statistical methodologies, including the Poisson

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distribution and homogeneous Markov chains, to predict and anticipate failures within the network, facilitating proactive maintenance and risk mitigation strategies [7].

Beyond enhancing safety, the Python-based safety scoring system is crucial for evaluating the feasibility and economic viability of hydrogen blending in pipeline transportation. By assessing hydrogen's potential as a clean energy carrier, the system supports the transition towards carbon neutrality [6]. Its ability to address safety challenges associated with hydrogen—particularly in production, storage, and transport—highlights the need for comprehensive risk analysis using advanced modeling techniques [1]. This aligns with the broader objective of exploring key safety technologies and advancements in the long-distance transportation of hydrogen-doped natural gas, addressing significant safety and technical challenges posed by hydrogen blending [3].

The development and application of this Python-based safety scoring system provide an effective tool for enhancing the safety and integrity of urban gas pipeline networks, particularly in the transportation of hydrogen-blended natural gas. Leveraging advanced data-driven methodologies for integrity detection and risk assessment, it addresses critical factors such as pipeline material aging, failure mechanisms, and performance testing. By integrating statistical analyses and predictive modeling, it improves decision-making processes for pipeline management and rehabilitation, thus significantly contributing to the overall safety and reliability of urban gas distribution systems [4, 13, 7, 3].

1.3 Structure of the Survey

This survey is systematically organized into several key sections to comprehensively address the multifaceted aspects of urban polyethylene (PE) gas pipeline safety and hydrogen-blended natural gas transportation. The paper begins with an **Introduction**, which highlights the significance of safety and integrity in these systems, followed by an overview of a Python-based safety scoring system.

The **Background and Core Concepts** section provides foundational knowledge on urban PE gas pipelines, elucidates the concept and benefits of hydrogen-blended natural gas, and defines essential terms such as pipeline integrity and safety risk analysis. This sets the stage for understanding the subsequent discussions.

In the section titled , the survey offers a comprehensive analysis of the technical and safety challenges associated with the transportation of hydrogen-blended natural gas. It emphasizes critical issues regarding material compatibility and the necessity for standardized testing protocols for metals and non-metallic materials in hydrogen environments. The review also discusses advancements in pipeline integrity assessment technologies and the development of monitoring systems for leakage and risk assessment. Additionally, it examines recent research and technological innovations aimed at optimizing transportation processes and enhancing safety measures, thereby supporting the integration of hydrogen into existing natural gas infrastructure [14, 6, 3, 11].

The section on **Safety Risk Analysis and Scoring Systems** explores various risk assessment frameworks and methodologies, detailing the development and application of a Python-based safety scoring system and its role in evaluating pipeline integrity and safety risks.

The survey thoroughly examines , emphasizing critical safety issues such as hydrogen-induced material degradation and the increased risks of leakage in hydrogen-blended systems. It delves into the mechanisms of hydrogen damage to pipeline materials, the challenges of ensuring the compatibility of non-metallic sealing materials, and the need for advanced non-destructive testing technologies. Furthermore, it reviews effective strategies for maintaining pipeline integrity, including optimizing operating conditions, enhancing leak detection systems, and developing materials with improved resistance to hydrogen embrittlement, all essential for the safe operation of hydrogen-blended natural gas pipelines [14, 15, 12].

In the section titled , a variety of real-world examples and demonstration projects illustrate the practical implementation of hydrogen-blended natural gas systems. These case studies highlight the operational challenges and safety considerations associated with hydrogen integration in natural gas pipelines while assessing the effectiveness of safety scoring systems designed to evaluate pipeline integrity and mitigate risks, thereby providing valuable insights for enhancing safety protocols in the evolving energy landscape [14, 12, 7].

The synthesizes the principal findings of the survey, underscoring the critical role of safety and integrity in the transportation of hydrogen-blended natural gas. It highlights the heightened safety challenges posed by this mixed transportation method and the necessity for robust safety technologies and standards. Additionally, the conclusion advocates for future research initiatives aimed at improving safety scoring systems and enhancing overall safety protocols associated with hydrogen-blended natural gas pipelines, including the development of advanced monitoring techniques and the establishment of unified standards for material compatibility and risk assessment [1, 12, 3, 14, 16].The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Urban PE Gas Pipelines in Gas Distribution Networks

Urban polyethylene (PE) gas pipelines are integral to natural gas distribution, underpinning urban energy infrastructure by facilitating efficient transport in high-demand areas. Their operation is governed by nonlinear flow dynamics, modeled by barotropic Euler equations with friction, ensuring system reliability [17]. Effective inspection and maintenance are crucial for mitigating risks and enhancing operational efficiency [18]. However, variables like public holidays complicate predictive models, requiring advanced techniques to manage consumption variability [19].

Challenges such as data sparsity and privacy issues impede accurate gas usage estimation, but hierarchical federated learning frameworks offer solutions by enabling collaborative model training while preserving privacy [20]. Hydrogen integration into existing networks introduces additional challenges related to material compatibility and public safety [9]. Environmental factors significantly influence pipeline safety, as highlighted by risk assessments of segments like the Wampu-Pasar IX pipeline [2]. Frequent underground pipeline incidents necessitate robust safety measures to prevent human and economic losses [5]. Aging PE materials further complicate these challenges, necessitating comprehensive performance testing and life prediction to maintain network integrity [4].

2.2 Hydrogen-Blended Natural Gas: Concept and Benefits

Hydrogen-blended natural gas strategically integrates hydrogen into existing pipelines, enhancing combustion efficiency and reducing emissions [21]. This approach addresses geographical mismatches between hydrogen production and consumption, facilitating efficient long-distance transport [22]. By leveraging existing infrastructure, hydrogen blending offers a cost-effective transition to cleaner energy systems, overcoming limitations of current hydrogen transport technologies [23]. Typically, hydrogen is blended at 3

Despite its advantages, hydrogen blending poses challenges, including leakage risks and material compatibility issues [3]. Extensive studies on material compatibility emphasize the need for defect detection techniques [14]. Improved monitoring and risk assessment methods are essential for safe operations [3]. Exploring green and blue hydrogen pathways reveals significant implications for the energy transition [24]. Reassigning natural gas pipelines for hydrogen transport is crucial, with economic potential underscored by cost functions [10].

Hydrogen-blended natural gas advances sustainable energy goals by leveraging existing infrastructure to reduce emissions. Research indicates blending hydrogen up to 20

2.3 Key Terms: Pipeline Integrity and Safety Risk Analysis

Pipeline integrity and safety risk analysis are vital for efficient urban gas distribution, especially with hydrogen-blended systems. Pipeline integrity involves systematic processes like defect detection and threat classification to ensure effective operation without failure [8]. Predictive and management strategies are necessary due to the random nature of failures, often caused by mechanical damage [7]. Safety risk analysis evaluates potential operational hazards, with hydrogen integration introducing complexities such as uneven concentration distribution, impacting efficiency and safety [22]. Hydrogen's properties challenge current transportation methods, leading to potential inefficiencies [23].

Integrity assessments focus on how hydrogen affects material safety, with risks like embrittlement and degradation compromising mechanical properties [3]. Current models often rely on subjective expert opinions, complicating accurate diagnosis and risk mitigation [25]. Comprehensive risk analysis frameworks are essential for ensuring hydrogen-blended pipelines' reliability and safety, addressing material compatibility, non-destructive testing, and performance evaluation while mitigating risks from failures and environmental hazards [14, 7, 26].

In recent years, the transportation of hydrogen-blended natural gas has garnered significant attention due to its potential to enhance energy efficiency and reduce carbon emissions. However, this transition is not without its challenges. Figure 2 illustrates the hierarchical structure of these challenges, material concerns, and innovations in hydrogen-blended natural gas transportation. The figure highlights various technical challenges, material compatibility issues, and ongoing research efforts that are critical to advancing this field. By examining these interconnected aspects, we can better understand the complexities involved and the necessary steps towards effective implementation.

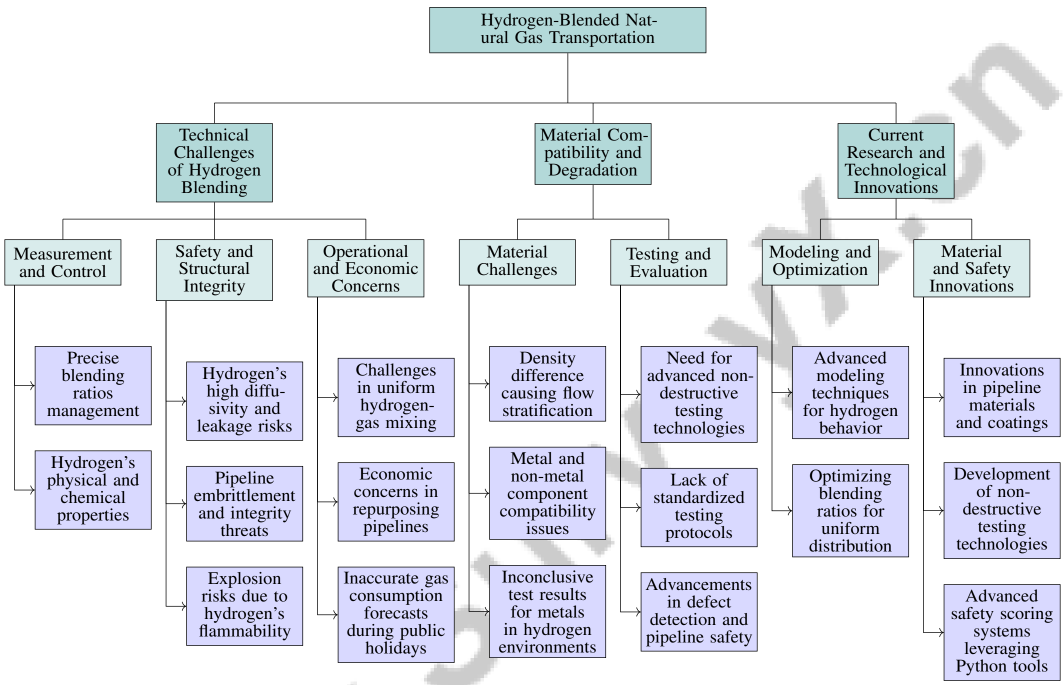


Figure 2: This figure illustrates the hierarchical structure of challenges, material concerns, and innovations in hydrogen-blended natural gas transportation, highlighting technical challenges, material compatibility issues, and current research efforts.

3 Hydrogen-Blended Natural Gas Transportation

3.1 Technical Challenges of Hydrogen Blending

Integrating hydrogen into natural gas networks presents significant technical challenges crucial for safe and efficient transport. A key issue is the precise measurement and control of hydrogen blending ratios, essential for managing hydrogen's physical and chemical properties within gas systems [11]. Hydrogen's high diffusivity exacerbates leakage risks and potential embrittlement, threatening pipeline integrity [22]. The interaction between blending ratios, inlet pressure, and pipeline throughput complicates predictions of line pack and storage capacity, which are vital for operational planning and safety [26]. Current methods struggle to achieve uniform hydrogen-gas mixing, leading to inefficiencies and increased risks [21]. Hydrogen's flammability and gas diffusion complexities in confined spaces elevate explosion risks, necessitating improved safety protocols and technologies [12]. The faster diffusion of hydrogen compared to natural gas heightens risks in buried pipelines, requiring advanced monitoring and control systems [15]. Existing monitoring techniques often fall short within complex buried pipeline structures, complicating hydrogen-blended network management [27]. Economic concerns persist regarding repurposing natural gas pipelines for hydrogen amid decarbonization efforts [10]. Additionally, rigid proximity classifications during public holidays may lead to inaccurate gas consumption forecasts [19].

To illustrate these challenges comprehensively, Figure 3 depicts the primary technical challenges associated with hydrogen blending in natural gas networks. This figure focuses on measurement and control, pipeline integrity, and economic and operational aspects. Each category highlights key issues and references relevant studies, providing a comprehensive overview of the obstacles to integrating hydrogen into existing infrastructure. Despite these challenges, recent studies propose approaches to maintain structural properties while achieving computational efficiency, critical for practical gas network applications [17]. Addressing these technical obstacles is imperative for successful hydrogen integration into natural gas systems, leveraging existing infrastructure to facilitate hydrogen delivery and reduce emissions [23].

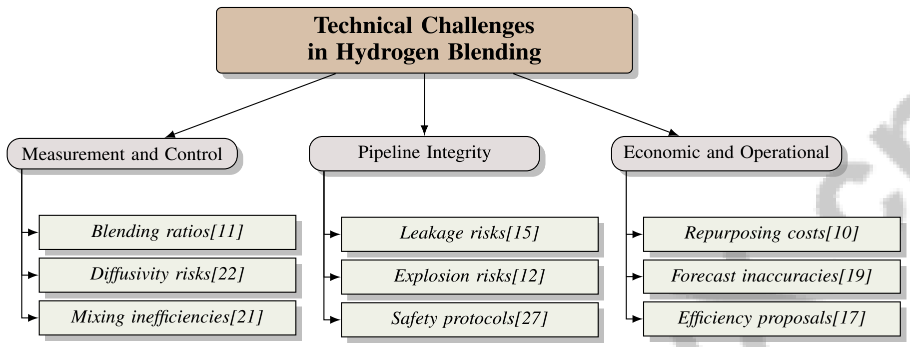


Figure 3: This figure illustrates the primary technical challenges associated with hydrogen blending in natural gas networks, focusing on measurement and control, pipeline integrity, and economic and operational aspects. Each category highlights key issues and references relevant studies, providing a comprehensive overview of the obstacles to integrating hydrogen into existing infrastructure.

3.2 Material Compatibility and Degradation

Incorporating hydrogen into natural gas systems raises significant concerns about material compatibility and degradation due to hydrogen's distinct properties. The density difference between hydrogen and natural gas can cause flow stratification and uneven mixing, risking localized hydrogen concentrations exceeding safe operational limits [22]. Material compatibility, particularly with metal and non-metal components, remains a pressing challenge. Inconclusive test results for metals in hydrogen environments complicate long-term performance assessments, while research on non-metallic sealing materials is insufficient, leaving gaps in understanding their behavior under hydrogen exposure [14]. The degradation of materials due to hydrogen exposure is further complicated by the lack of advanced non-destructive testing technologies essential for defect detection and failure prevention in hydrogen-blended systems. Existing methods for evaluating pipeline defects are still developing, limiting proactive risk management for hydrogen-induced degradation [14]. Addressing these challenges requires advancing research in material science and testing technologies. Establishing robust non-destructive evaluation techniques and thorough compatibility assessments is crucial for safe and efficient hydrogen-blended natural gas pipeline operations. This is vital given the risks of hydrogen embrittlement and the need for standardized testing protocols to assess material integrity. Advancements in non-destructive testing technologies and understanding the mechanical properties of materials in hydrogen environments are essential for enhancing defect detection accuracy and overall pipeline safety [15, 4, 22, 3, 14]. Such advancements will enhance infrastructure resilience and facilitate broader hydrogen adoption as a sustainable energy carrier.

3.3 Current Research and Technological Innovations

Recent advancements in hydrogen-blended natural gas transportation focus on addressing challenges posed by hydrogen's unique properties and integration into existing infrastructure. Key research areas involve developing advanced modeling techniques to predict hydrogen behavior within gas systems, optimizing blending ratios to ensure uniform distribution and minimize localized hydrogen concentrations that could lead to operational hazards [11]. Innovations in pipeline materials and coatings are prominent, aiming to enhance compatibility with hydrogen by investigating materials that can withstand hydrogen-induced degradation, thereby extending pipeline lifespan and safety [14]. The development of non-destructive testing technologies is crucial, providing means to detect early signs of material degradation and prevent failures [14]. Research also explores the economic and logistical implications of hydrogen blending, assessing the feasibility of repurposing natural gas pipelines for hydrogen transport. Studies highlight potential cost savings and efficiency gains from utilizing current infrastructure, while identifying the need for strategic investments in monitoring and control systems to manage hydrogen's unique challenges [10]. Technological innovations focus on enhancing safety protocols and risk assessment frameworks. Advanced safety scoring systems, often leveraging Python-based computational tools, have been developed to evaluate the integrity of hydrogen-blended pipelines, incorporating real-time data to predict and mitigate potential risks [11]. These systems are integral to ensuring the safe and efficient operation of gas distribution networks as the energy sector transitions towards more sustainable practices.

4 Safety Risk Analysis and Scoring Systems

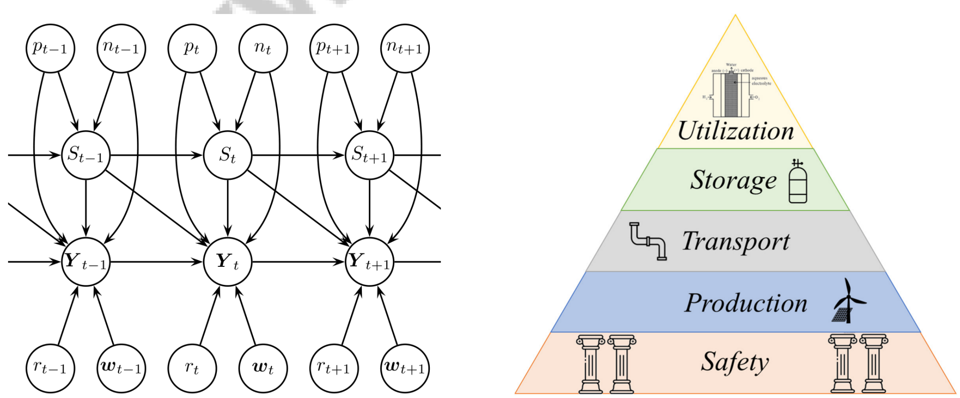
4.1 Risk Assessment Frameworks and Methodologies

Benchmark	Size	Domain	Task Format	Metric

Table 1: The table provides an overview of representative benchmarks used in risk assessment frameworks for hydrogen-blended natural gas pipelines. It details the size, domain, task format, and metrics associated with each benchmark, offering insights into their application and relevance in safety evaluations.

Advanced risk assessment frameworks are essential for managing safety risks in hydrogen-blended natural gas pipelines, addressing the unique challenges of hydrogen's properties [3]. The Pipeline Integrity Management System (PIMS) offers a comprehensive lifecycle approach to pipeline integrity, ensuring a holistic risk management strategy [2]. Models like T-type and variable diameter blending pipeline models assess hydrogen's distribution and flow behavior, providing insights to maintain safe operational parameters [22]. Safety assessments and feasibility studies underscore the need for robust standards and technologies in hydrogen blending [14]. Enhanced mixing techniques, such as the helical static mixer, improve risk assessment by ensuring better hydrogen-natural gas mixing [21].

Failure data analysis enhances network management decision-making by predicting potential failures [7]. Evaluation methods using leave-one-out cross-validation assess performance on classification accuracy and threat detection [8]. The Bivariate Nonparametric Stochastic Safety Risk Generator (BNSR) models construction safety risks using textual injury reports, employing Kernel Density Estimators and Copulas [25]. Economic considerations in risk assessment frameworks highlight cost reductions from pipeline repurposing for hydrogen transport, crucial for strategic planning [10].



(a) A Graphical Model for Time Series Analysis[19]

(b) The image represents a pyramid diagram illustrating the hierarchy of hydrogen energy systems.[1]

Figure 4: Examples of Risk Assessment Frameworks and Methodologies

As shown in Figure 4, diverse risk assessment methodologies are crucial for hazard evaluation and safety measure implementation. The "Graphical Model for Time Series Analysis" predicts risks over time by mapping data flows, while the pyramid diagram outlines hydrogen energy systems' hierarchy, emphasizing safety and utilization [19, 1]. Additionally, Table 1 presents a comprehensive summary of the benchmarks integral to the risk assessment methodologies discussed, highlighting their characteristics and evaluative metrics.

4.2 Technological Innovations in Safety Risk Analysis

Technological innovations in safety risk analysis for hydrogen-blended natural gas pipelines focus on enhancing mixing uniformity and reducing pressure loss, as exemplified by the helical static mixer [21]. The Bucket Brigade-inspired Single Network Protocol (BSNP) minimizes electromagnetic interference and deployment costs in pipeline monitoring [28]. The SAFRAN method facilitates performance variability analysis, improving safety management [29].

Figure 5 illustrates the key technological innovations in safety risk analysis for hydrogen-blended natural gas pipelines, focusing on pipeline monitoring, material science advances, and the challenges of hydrogen blending. Materials science advancements have improved understanding of pipeline compatibility with hydrogen, leading to detection technologies that prevent material degradation [14]. Incorporating empirical data into safety assessments enhances modeling of complex dependencies, providing robust frameworks for evaluating hazards in hydrogen systems [25].

Comprehensive studies on hydrogen blending reveal operational challenges, such as reduced energy flow rates due to lower calorific value and impacts on compressors and pipeline conditions. These studies, which include mathematical modeling of Hydrogen-Blended Natural Gas (HBNG) transportation, offer insights into the feasibility and safety of hydrogen infrastructure [14, 26, 23, 22].

Innovations like the SAFRAN method, specialized event databases, and statistical modeling of failures highlight the importance of sophisticated modeling and monitoring in refining safety risk frameworks. These methodologies enhance safety systems and offer insights for preventing incidents and mitigating risks in hydrogen energy and gas distribution [16, 7, 29]. Addressing hydrogen blending's challenges, these innovations improve gas distribution network safety and reliability.

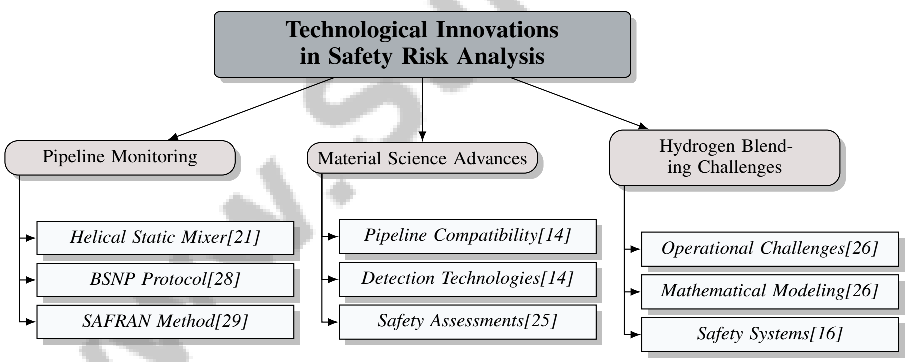


Figure 5: This figure illustrates the key technological innovations in safety risk analysis for hydrogen-blended natural gas pipelines, focusing on pipeline monitoring, material science advances, and the challenges of hydrogen blending.

5 Hydrogen Safety and Pipeline Integrity

5.1 Hydrogen-Induced Material Degradation

Integrating hydrogen into natural gas pipelines presents challenges due to hydrogen's propensity to cause material degradation, notably hydrogen embrittlement. This phenomenon, where hydrogen atoms infiltrate metal lattices, compromises ductility and increases cracking susceptibility under stress, necessitating standardized tests for material compatibility in hydrogen environments [14]. High-performance non-metallic materials are pivotal for maintaining pipeline integrity, given their resistance to hydrogen-induced degradation [14]. The economic benefits of hydrogen blending may be offset by increased operational and maintenance costs, highlighting the need for comprehensive safety assessments and robust data on long-term impacts [23]. Advanced non-destructive testing tools are essential for early detection of material degradation, supporting proactive maintenance strategies [14]. Optimizing compressor performance under variable hydrogen concentrations is a promising research area to enhance transportation efficiency and safety [23].

5.2 Leakage Risks and Detection Methods

Hydrogen's small molecular size increases leakage risks in natural gas pipelines, necessitating advanced detection methods due to its high permeability [3]. Buried pipelines are particularly vulnerable, as hydrogen's rapid diffusion heightens explosion risks in confined spaces [15]. Current detection methods are often inadequate for complex underground networks [27]. The development of smart utility meters and intelligent monitoring systems is crucial for enhancing leak detection, enabling real-time monitoring and rapid hazard response [27]. These systems utilize advanced sensors and data analytics for continuous surveillance and early leak warnings, improving safety and operational efficiency.

Figure 6 illustrates the key aspects of hydrogen leakage risks and detection methods in natural gas pipelines, highlighting advanced detection technologies, safety strategies, and operational enhancements. This visual representation underscores the importance of robust safety protocols and emergency response strategies essential for mitigating leakage risks, including comprehensive risk assessment frameworks that account for hydrogen's diffusivity and flammability [3]. Research into material compatibility and degradation effects is vital for addressing leakage risks, with innovative materials and coatings enhancing pipeline integrity [14]. A comprehensive strategy integrating advanced detection technologies, meticulous safety planning, and innovative material development is critical due to hydrogen's unique properties and explosion risks in high-pressure environments. Effective strategies should include standardized testing protocols, improvements in non-destructive testing methods, and the development of low-permeability, corrosion-resistant materials. Optimizing operational conditions and implementing robust ventilation strategies in utility tunnels can enhance safety and minimize leakage risks [14, 15, 16, 12].

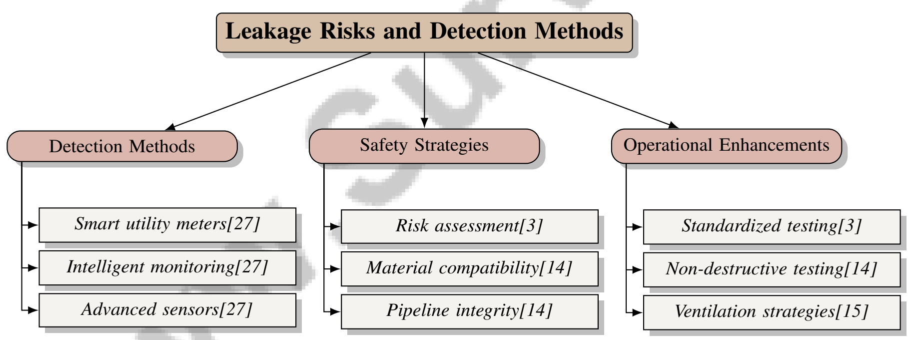


Figure 6: This figure illustrates the key aspects of hydrogen leakage risks and detection methods in natural gas pipelines, highlighting advanced detection technologies, safety strategies, and operational enhancements.

5.3 Strategies for Maintaining Pipeline Integrity

Ensuring the integrity of pipelines for hydrogen-blended natural gas is crucial for safety and operational efficiency. Advanced risk assessment models reduce uncertainty and improve failure prediction accuracy by evaluating varying risk levels under different measurement functions, facilitating targeted maintenance interventions [13]. A comprehensive risk management approach is necessary, integrating technical and policy-oriented strategies. Enhancements in hydrogen production efficiency impact the feasibility and safety of hydrogen blending, while supportive policies and international agreements facilitate trade and ensure consistent safety standards [24]. Material innovations are critical, with research advancing high-performance materials resistant to hydrogen degradation. Standardized compatibility tests for metals in hydrogen-blended pipelines are urgently needed, as current evaluations lack clarity on hydrogen's effects. Improved non-metallic sealing materials and low-permeability, corrosion-resistant pipelines are essential. Advancements in non-destructive testing technologies enhance defect detection accuracy, with methodologies for assessing pipeline defects still being refined [14, 4]. Advanced coatings and sealing technologies mitigate embrittlement effects and prevent leaks, extending pipeline lifespan. Real-time monitoring systems utilizing advanced sensors, such as fiber optic distributed acoustic sensing (DAS) and phase-sensitive optical time-domain reflectometry (-OTDR), are crucial for early detection of degradation and operational anomalies, enhancing integrity management of critical infrastructure [8, 30].

6 Case Studies and Applications

6.1 Demonstration Projects

Demonstration projects play a pivotal role in illustrating the practical integration of hydrogen-blended natural gas systems, offering valuable insights into operational dynamics and safety protocols. The Chaoyang Hydrogen Blending Demonstration Project in Liaoning, China, serves as a model by employing renewable energy for hydrogen production to integrate it safely with natural gas, setting a precedent for future projects [11]. Similarly, the HyDeploy Project in the UK explores the safe inclusion of up to 20

Recent studies on helical static mixers demonstrate their capability to enhance hydrogen-blended systems by improving mixing efficacy and mitigating risks linked to uneven hydrogen distribution [21]. A comprehensive survey of global research and demonstration projects underscores hydrogen blending's strategic role in sustainable energy transitions [6]. Additionally, experiments with realistic gas network benchmarks have validated proposed methods over traditional non-structure-preserving reduction techniques, highlighting successful implementations and the potential for optimized network operations [17]. Collectively, these demonstration projects offer a robust framework for understanding hydrogen blending complexities and facilitate future advancements in the field.

6.2 Innovative Safety Applications

Innovative safety applications are vital for addressing challenges in integrating hydrogen-blended natural gas into pipeline systems. Transitioning to a hydrogen economy demands technological innovations, strategic governmental support, and policy frameworks that foster safety and innovation in hydrogen-related initiatives [16]. Advanced data management systems, such as the hierarchical federated learning framework HI-GAS, enhance pipeline safety by incentivizing high-quality data contributions while ensuring equitable reward distribution and addressing data privacy and sparsity issues in gas networks [20].

Strategic network inspection methodologies optimize resource allocation for pipeline maintenance and security, with recent experiments providing practical guidelines for real-world applications. These emphasize the necessity of location-specific inspections to mitigate risks and enhance operational efficiency [18]. Numerical studies also offer recommendations for improving pipeline safety in the context of hydrogen blending, advocating optimized operating conditions and advanced leak detection systems, which are crucial for accident prevention and ensuring gas distribution network integrity [15]. These innovative safety applications are essential for overcoming the technical and safety challenges of hydrogen-blended natural gas, supporting the broader transition to sustainable energy systems.

7 Conclusion

Ensuring safety and integrity in urban polyethylene (PE) gas pipelines and hydrogen-blended natural gas systems is paramount due to the unique challenges they pose, such as material degradation and leakage risks. The successful integration of hydrogen into existing natural gas networks hinges on adherence to local standards and infrastructure capabilities. A Python-based safety scoring system has proven to be an effective tool for assessing pipeline integrity and associated risks, thereby enhancing the reliability of gas distribution networks.

Future research should aim to optimize blending technologies and establish comprehensive standards for hydrogen integration in natural gas systems. This includes advancing safety regulations, improving personnel training, and leveraging computational fluid dynamics (CFD) simulations to enhance safety measures in hydrogen applications. It is also crucial to refine simulation models to incorporate a wider range of variables and conduct field tests for validation. Expanding datasets to include diverse materials and operational scenarios is essential for the successful integration of hydrogen into energy systems.

The HI-GAS mechanism holds promise for improving gas usage estimation accuracy and reducing operational costs through incentivized data contribution and federated learning. Further investigation is needed to understand the impact of varying operational conditions on the efficiency of hydrogen-blended natural gas pipelines and to refine models to account for complex variable interactions. Establishing international standards for material compatibility testing and developing advanced non-metallic materials are critical for enhancing defect detection technologies tailored for hydrogen environments.

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