
Urban Gas Pipelines and Hydrogen Integration: A Survey

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Abstract

The integration of hydrogen as a blended fuel in urban gas pipelines signifies a critical advancement in the transition towards sustainable energy systems. This survey paper explores the multifaceted aspects of incorporating hydrogen into existing energy infrastructures, focusing on safety, feasibility, and the structural integrity of pipelines. The research highlights hydrogen's potential to decarbonize energy systems, enhance energy security, and support renewable energy integration. Key challenges identified include the high costs of hydrogen production and storage, material compatibility issues, and the need for robust safety assessments due to hydrogen's unique properties. Technological advancements such as proton-exchange membrane fuel cells and innovative monitoring systems like the Innovative Acoustic Emission Method are pivotal in addressing these challenges. The survey underscores the importance of comprehensive policy and regulatory frameworks to facilitate hydrogen infrastructure development, emphasizing the need for continued research and collaboration. By overcoming technical and economic barriers, hydrogen-blended urban gas pipelines can significantly contribute to a sustainable and resilient energy future, aligning with global decarbonization goals. The findings advocate for a coordinated approach to hydrogen integration, leveraging technological innovations and strategic investments to ensure a seamless transition to hydrogen-enhanced energy systems.

1 Introduction

1.1 Contextualizing Urban Gas Pipelines and Hydrogen Integration

The integration of hydrogen as a blended fuel in urban gas pipelines marks a significant transformation in energy systems, supporting global sustainability efforts. Traditionally designed for natural gas, urban gas pipelines are being re-evaluated for their potential to transport hydrogen-blended fuels. This shift is driven by the imperative to decarbonize energy systems and enhance security, as evidenced by studies on hydrogen storage demands and their critical role in achieving a climate-neutral Europe [1]. The adaptation of existing infrastructure to accommodate hydrogen, which has distinct physical and chemical properties, presents complex challenges.

The integration of hydrogen via electrolysis into electricity systems, particularly in Germany, highlights significant implications for market dynamics and price signals [2]. Understanding these economic and operational impacts is crucial for hydrogen's role in urban gas networks. Additionally, the incorporation of fuel cells into microgrids illustrates both technological advancements and challenges faced during integration, emphasizing the multifaceted nature of hydrogen's incorporation into energy systems [3].

Significant research and development initiatives are underway to address the technical, economic, and regulatory challenges of hydrogen integration, facilitating a smooth transition to hydrogen-enhanced energy systems essential for meeting future energy demands. Projections suggest that hydrogen could fulfill up to 24% of global energy needs by 2050, necessitating the development of robust

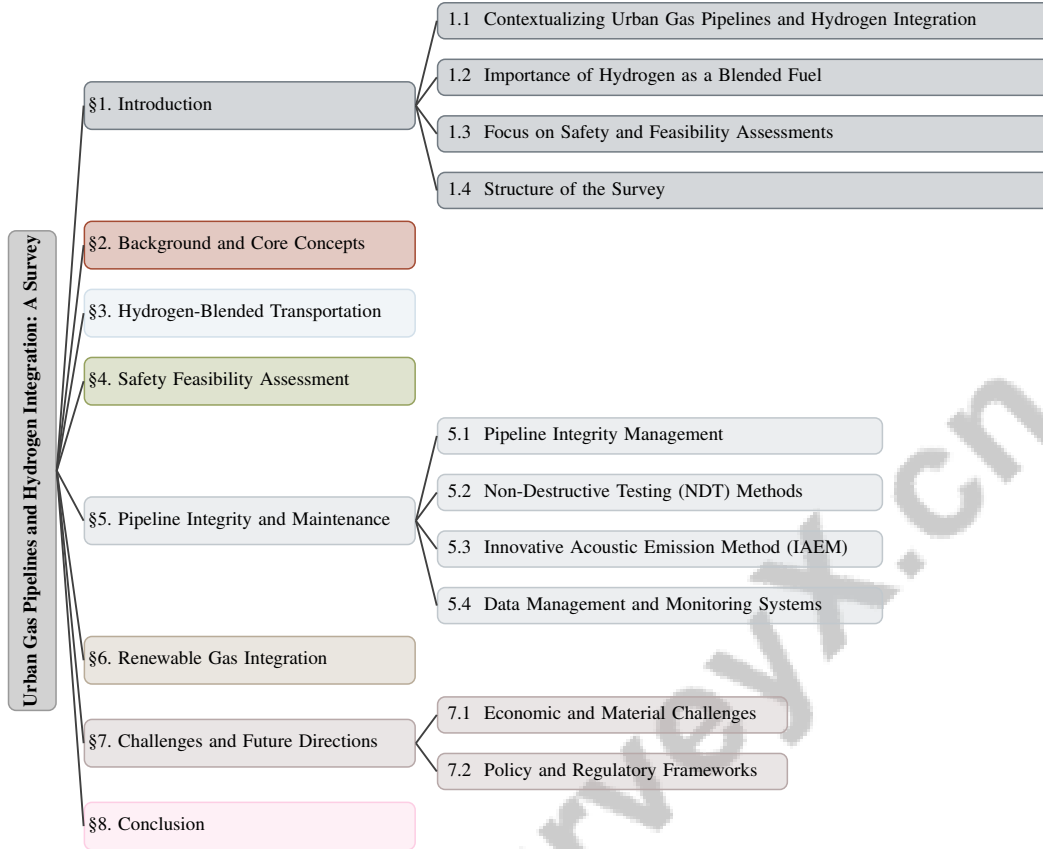


Figure 1: chapter structure

hydrogen infrastructure, including pipelines and storage solutions. Innovations in materials, such as polyethylene pipes, are critical for enhancing safety and reliability in urban gas networks, alongside the establishment of hydrogen production hubs to support diverse applications across heating, industry, and transportation sectors [4, 1, 5, 6, 7].

1.2 Importance of Hydrogen as a Blended Fuel

Integrating hydrogen as a blended fuel in energy systems is transformative for sustainability and carbon emission reduction. As a versatile energy carrier, hydrogen enhances energy efficiency and reliability, especially when combined with variable renewable energy sources. Its significance is particularly pronounced in sectors where direct electrification is challenging, providing a cost-effective method for CO₂ reduction [8].

The deployment of green hydrogen serves as both long-term energy storage and a fossil fuel substitute in hard-to-abate sectors, underscoring its vital role in decarbonization efforts [9]. Moreover, the development of an open-source model for analyzing hydrogen supply and demand across various sectors highlights the strategic importance of hydrogen infrastructure in optimizing energy systems [5].

Economically, integrating hydrogen into microgrids through fuel cells enhances power quality and reliability while offering significant energy efficiency benefits [3]. However, achieving these benefits requires overcoming infrastructural challenges, including the establishment of a robust hydrogen storage and distribution network essential for the widespread adoption of technologies like PEM fuel cells [10]. Timely investments in hydrogen infrastructure are crucial for meeting future demands and achieving climate neutrality by 2050 [1].

Additionally, strategic pricing mechanisms, such as nodal pricing, can optimize hydrogen production cost-effectiveness, reducing congestion costs and promoting production at low-cost nodes [2]. The

commercialization of fuel cells, which necessitates cost reduction and durability enhancements, further emphasizes hydrogen's potential as a sustainable fuel option in future energy systems [11].

1.3 Focus on Safety and Feasibility Assessments

Integrating hydrogen into existing urban gas pipeline systems requires a thorough evaluation of safety and feasibility. This assessment is vital to ensure that hydrogen can be blended with natural gas without compromising infrastructure integrity. Key challenges include the high costs and low durability of fuel cells, which are crucial for hydrogen conversion and utilization in microgrids [3]. Addressing these challenges necessitates robust control systems and optimized integration to maintain operational efficiency and safety.

The decarbonization of energy systems, particularly in sectors where direct electrification is impractical, highlights the need for a flexible and integrated energy system incorporating hydrogen as a clean energy carrier [8]. This flexibility is essential for adapting to varying sector demands and ensuring a stable energy supply. The feasibility of hydrogen integration also hinges on retrofitting existing infrastructure, requiring careful assessments of material compatibility and the development of new technologies for monitoring pipeline integrity.

Safety assessments must account for hydrogen's unique properties, such as its lower ignition energy and broader flammability range compared to natural gas. Pipeline infrastructure faces specific challenges, including potential material degradation like cracks and pitting, necessitating comprehensive risk management strategies and advanced safety protocols. These measures are crucial for preventing accidents and ensuring public safety while maintaining the integrity of gas transportation systems. Proactive asset integrity management practices, including life cycle cost analysis-based decision support systems and in-line inspection techniques, enable pipeline operators to effectively monitor infrastructure health, minimizing risks and enhancing operational efficiency [12, 13, 14]. By addressing safety and feasibility challenges, hydrogen can be effectively integrated into urban gas pipelines, fostering a more sustainable and resilient energy system.

1.4 Structure of the Survey

This survey is systematically organized to explore the integration of hydrogen as a blended fuel in urban gas pipelines, emphasizing safety and feasibility. The paper begins with an **Introduction** that contextualizes the current state of urban gas pipelines and the significance of hydrogen integration, highlighting hydrogen's role as a sustainable fuel and the necessity for safety and feasibility assessments.

Following the introduction, the **Background and Core Concepts** section provides an overview of fundamental principles related to hydrogen-blended transportation, infrastructure, and pipeline integrity. It discusses renewable gas integration's role in transitioning to sustainable energy systems, laying a foundation for subsequent discussions.

The survey then examines **Hydrogen-Blended Transportation**, focusing on technological advancements and challenges in integrating hydrogen into urban gas pipelines. This section explores the benefits and potential risks of hydrogen blending in existing systems, supported by recent technological developments.

In the **Safety Feasibility Assessment** section, the survey analyzes safety considerations and feasibility of hydrogen integration, discussing methodologies for assessing pipeline integrity and risk management, with case studies illustrating successful safety assessments in hydrogen-blended systems.

The importance of pipeline integrity is further explored in the **Pipeline Integrity and Maintenance** section, reviewing current technologies and methods for inspection and maintenance, including advancements in non-destructive testing and data management systems to ensure pipeline safety.

The survey also addresses **Renewable Gas Integration**, focusing on the integration of renewable gases, including hydrogen, into urban energy systems. It examines hydrogen's critical role in decarbonizing energy systems by facilitating renewable energy integration, particularly in addressing seasonal variability in solar and wind power. Hydrogen's potential to replace fossil fuels in hard-to-abate sectors could lead to a 17% reduction in the levelized cost of a zero-carbon electricity system in China. The analysis emphasizes the economic and environmental benefits of coupling hydrogen

infrastructure with electricity systems, demonstrating that this integrated approach lowers overall energy costs and enhances energy security, making green hydrogen more competitive compared to traditional fossil fuel-based hydrogen options [9, 8].

Finally, the **Challenges and Future Directions** section identifies key challenges in developing and implementing hydrogen-blended urban gas pipelines, discussing potential solutions, future research directions, and the importance of policy and regulatory frameworks in supporting hydrogen infrastructure development. The survey concludes by summarizing the main findings, reflecting on hydrogen's transformative potential in urban gas pipelines, and emphasizing the need for continued research and collaboration to address identified challenges. The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Fundamental Concepts of Hydrogen-Blended Transportation

Integrating hydrogen into multi-energy systems marks a significant evolution in energy management, optimizing the use of renewable sources, batteries, and hydrogen production to enhance efficiency and sustainability [15]. Central to this is hydrogen's role as an energy vector within hybrid microgrids, facilitating diverse applications, particularly in transportation [6]. Hydrogen's versatility allows it to be stored and reconverted into electricity or used directly as fuel, providing a sustainable alternative to conventional energy sources [16]. This adaptability is crucial for stabilizing energy supply during fluctuating demand, enhancing system resilience. Strategic integration of hydrogen into multi-energy systems supports the transition to cleaner transportation, leveraging its high energy density to potentially meet 30% of transportation energy needs by 2050, especially in heavy-duty vehicles, while addressing renewable energy intermittency [15, 7, 8, 6].

2.2 Hydrogen Infrastructure and Optimization

Optimizing hydrogen infrastructure is vital for its integration into modern energy systems. Advances in proton-exchange membrane (PEM) fuel cells, known for their efficiency and adaptability, are essential for improving performance, reducing costs, and increasing durability [10]. Sophisticated models, such as multistage stochastic optimization, manage infrastructure components like electrolyzers and storage facilities to meet transportation demands [17]. Mathematical models for designing optimal renewable energy transport infrastructure are crucial for efficient hydrogen integration, considering various transport technologies and their interactions [18]. Coupling hydrogen with electricity and hard-to-abate sectors enhances efficiency and cost-effectiveness, underscoring the strategic role of infrastructure development in supporting hydrogen's energy transition [9, 5]. Effective infrastructure development and optimization are critical for adopting hydrogen as a sustainable energy carrier, addressing diverse production methods and supply-demand dynamics. Establishing green hydrogen hubs and expanding storage and pipeline networks are crucial for meeting future energy targets and integrating hydrogen into energy systems, supporting a low-carbon economy transition by 2050 [18, 1, 5, 9, 7].

2.3 Pipeline Integrity and Energy Systems

Ensuring pipeline integrity is fundamental for integrating hydrogen into energy systems, given the challenges posed by renewable energy variability and hydrogen demand uncertainty [17]. Advanced methodologies are required for pipeline monitoring, particularly in harsh environments, where robust sensing and data acquisition systems are vital for real-time condition monitoring and proactive maintenance [19]. Integrating hydrogen into existing networks necessitates a comprehensive integrity management approach, including developing materials and technologies that withstand hydrogen's unique properties. Advanced inspection techniques, such as non-destructive testing (NDT) methods like magnetic flux leakage (MFL) and ultrasonic testing (UT), are critical for assessing structural integrity, identifying defects that could compromise safety and reliability. Utilizing integrated systems like Pipeline Inspection Gauges (PIGs) and robotic inspection technologies enhances operational safety and maintenance, addressing environmental and mechanical stress challenges [14, 20]. Maintaining pipeline integrity is crucial for hydrogen integration into energy systems, improving transportation safety and efficiency across sectors. With hydrogen projected to meet up to 25% of

future energy demands in the EU by 2050, investments in infrastructure, such as green hydrogen hubs and advanced storage solutions, are essential for accommodating growth and ensuring a reliable energy supply [2, 1, 5, 6, 7].

In recent years, the exploration of hydrogen-blended transportation has garnered significant attention due to its potential to revolutionize the energy sector. This review aims to elucidate the various dimensions of hydrogen blending, particularly emphasizing its technological advancements and associated benefits and risks. As illustrated in Figure 2, the hierarchical structure of hydrogen-blended transportation is meticulously organized to showcase key innovations and integration strategies under the technological advancements category. Furthermore, the figure delineates the benefits of energy cost reduction and decarbonization, alongside the critical considerations of safety and material compatibility risks. This comprehensive framework not only enhances our understanding of the current landscape but also underscores the complexities involved in the implementation of hydrogen blending in transportation systems.

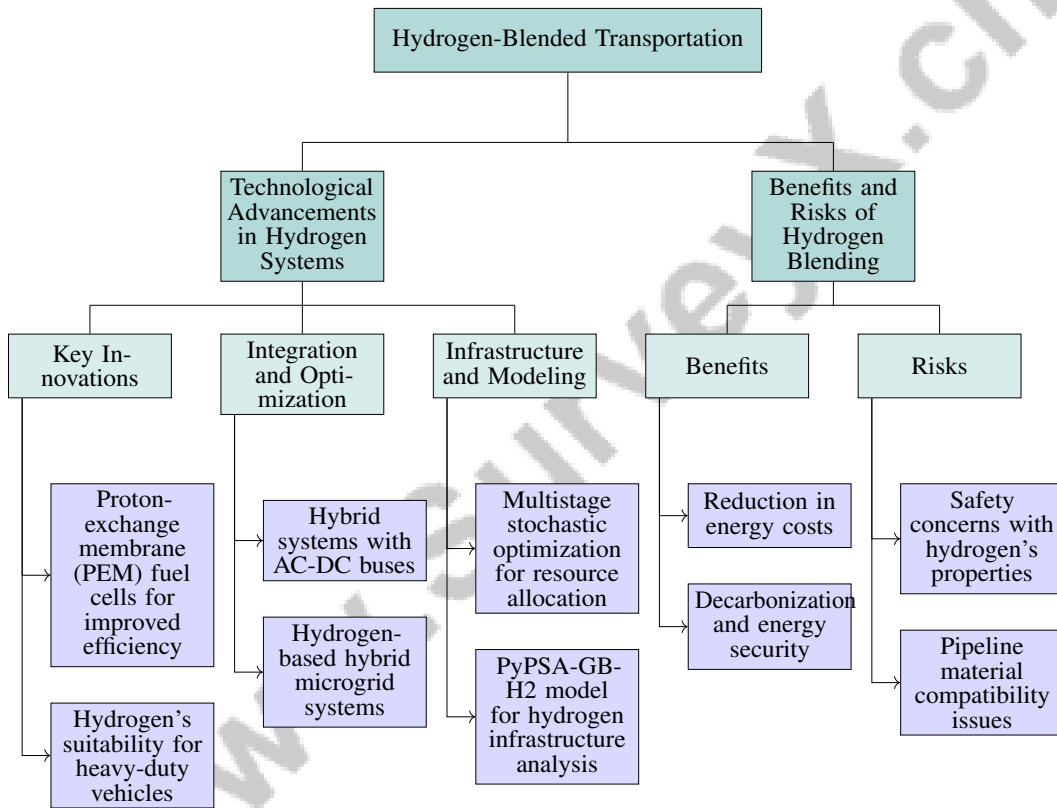


Figure 2: This figure illustrates the hierarchical structure of hydrogen-blended transportation, focusing on technological advancements and the benefits and risks of hydrogen blending. Key innovations, integration strategies, and infrastructure models are categorized under technological advancements, while energy cost reduction and decarbonization benefits, as well as safety and material compatibility risks, are highlighted under the benefits and risks section.

3 Hydrogen-Blended Transportation

3.1 Technological Advancements in Hydrogen Systems

Recent advancements in hydrogen technologies have significantly enhanced its integration into energy systems, marking a pivotal shift towards sustainable energy solutions. Key innovations include the development of proton-exchange membrane (PEM) fuel cells, which have improved efficiency in both transportation and stationary power generation. Hydrogen's high gravimetric energy density makes it particularly suitable for heavy-duty vehicles (HDVs) such as trucks, buses, locomotives, and marine

transport. As nations develop hydrogen economy roadmaps, investments in research for hydrogen production, storage, and infrastructure are crucial. Projections suggest that by 2050, hydrogen could meet up to 24% of global energy demands, with 30% of this share expected for transportation. To support this growth, advancements in fuel cell technology, materials, and the establishment of green hydrogen hubs with flexible infrastructure are essential [5, 7].

The integration of hydrogen into multi-energy systems is further enhanced by hybrid systems utilizing AC-DC hybrid buses, optimizing hydrogen output and overall system performance [15]. Additionally, hydrogen-based hybrid microgrid systems incorporating renewable energy sources, such as solar and wind, employ advanced control strategies for power flow management and stability maintenance [6].

Innovative multistage stochastic optimization approaches have refined the management of hydrogen production and costs by considering uncertainties in renewable energy generation and hydrogen demand, thus optimizing resource allocation [17]. The PyPSA-GB-H2 model represents a significant advancement, providing comprehensive analyses of hydrogen infrastructure with high temporal and spatial resolution, aiding in understanding the complexities of hydrogen integration [5].

Advancements in energy system models have enabled a more integrated assessment of heat and electricity sectors, particularly through bidirectional linking, highlighting the synergies between these sectors and the role of hydrogen in decarbonization efforts [21].

Technological developments in hydrogen systems underscore its transformative potential in energy frameworks, offering a sustainable pathway to meet future energy demands. Advancements in hydrogen production, storage, and fuel cell technology not only enhance hydrogen's role as a critical energy carrier but also facilitate its adoption across various sectors, including transportation, industry, and electricity generation. With expectations that hydrogen may fulfill up to 24% of global energy needs by 2050, substantial investments and infrastructure enhancements are underway to bolster its integration into heavy-duty transportation and other applications, including the establishment of green hydrogen hubs and improved storage solutions to address seasonal variability in renewable energy and achieve decarbonization targets [1, 5, 11, 7, 9].

3.2 Benefits and Risks of Hydrogen Blending

Blending hydrogen with natural gas in urban pipeline systems offers notable advantages while presenting potential risks that need to be managed for optimal energy system performance. A primary benefit is the reduction in energy costs, as hydrogen serves as both a storage medium and a fuel, enhancing system efficiency by allowing excess renewable energy to be stored as hydrogen for use during peak demand, thereby stabilizing the energy supply [9].

Hydrogen blending also aids in decarbonizing energy systems by reducing carbon emissions associated with natural gas consumption. Integrating hydrogen into existing natural gas pipelines allows for a gradual transition to cleaner energy sources without extensive infrastructure changes. This strategy significantly reduces greenhouse gas emissions and enhances energy security by diversifying the energy mix, positioning hydrogen as a long-duration energy storage solution. This diversification reduces reliance on fossil fuels and supports the transition toward a zero-carbon energy system, particularly in sectors challenging to electrify directly. Moreover, leveraging hydrogen infrastructure can lower overall energy system costs and improve renewable energy integration efficiency, contributing to a more resilient and sustainable energy landscape [9, 5, 8].

However, blending hydrogen with natural gas introduces risks that require careful management to ensure safe and efficient operations. The complexities of hydrogen infrastructure development, varying production technologies, and the need for robust safety measures in high-capacity storage and transport systems necessitate addressing these risks as hydrogen becomes integrated into sectors such as heating, industry, and transportation [1, 5, 9, 7, 8]. The distinct physical and chemical properties of hydrogen, including its lower ignition energy and wider flammability range compared to natural gas, increase the risks of leaks and combustion incidents. Thus, rigorous safety assessments and advanced monitoring and control systems are essential for effective hazard detection and mitigation.

The compatibility of existing pipeline materials with hydrogen is another critical concern, necessitating thorough evaluation of pipeline integrity to address issues such as material degradation, cracking, and pitting. Recent advancements in acoustic emission monitoring techniques highlight the importance of understanding failure mechanisms in various pipeline materials, including both

long-term used and new ferritic steel, to ensure safe hydrogen transportation and maintain the operational reliability of gas infrastructure [7, 14]. Hydrogen can induce embrittlement in certain metals, posing risks to pipeline integrity and leading to potential failures. Therefore, comprehensive material assessments and the development of new technologies for pipeline maintenance and monitoring are crucial for managing these risks.

4 Safety Feasibility Assessment

4.1 Hydrogen Infrastructure and Risk Assessment

Integrating hydrogen infrastructure into energy systems requires a robust risk assessment framework to address the challenges posed by hydrogen's unique properties. The stochastic nature of renewable energy and the need for efficient storage solutions are pivotal in developing effective risk assessment methodologies [16]. The complexities of hydrogen infrastructure are heightened by the necessity for systematic integrity evaluation technologies, particularly for polyethylene (PE) pipes, which face challenges due to environmental variability and difficulties in accurately predicting pipeline lifespan [4]. Multistage stochastic optimization methodologies, employing decomposition techniques, are utilized to address these challenges, essential for infrastructure planning and risk management [5]. Furthermore, integrating hydrogen into hybrid energy systems provides an operational framework that enhances reliability and informs risk assessment methodologies [16].

A structured risk assessment approach involves three main steps: defect detection and identification, defect growth prediction, and risk-based management [22]. This framework is crucial for maintaining pipeline integrity, as timely detection and monitoring of defects are fundamental to preventing safety hazards. Innovative methods for early material degradation detection improve safety management by enabling more prompt interventions than traditional techniques [4]. Evaluating performance metrics for hydrogen systems—including durability, efficiency, and scalability—is vital to ensure infrastructure meets heavy-duty application demands [9]. Critiques of hydrogen infrastructure, particularly regarding fuel cell commercialization challenges, underscore significant safety considerations in hydrogen integration [11]. By leveraging diverse methodologies and addressing these challenges, stakeholders can formulate robust risk management strategies that promote the safe and efficient integration of hydrogen into energy systems.

4.2 Case Studies and Methodological Approaches

The safety assessment of hydrogen systems has been significantly enhanced by innovative in-line inspection (ILI) tools and methodologies, pivotal for defect detection and management. These advancements improve safety and reliability in pipeline operations by enabling more accurate identification and classification of potential threats [13]. A notable methodological advancement includes a novel pipeline integrity threat detection system, which has demonstrated substantial improvements in classification accuracy and threat detection capabilities compared to earlier methods [22]. In non-destructive testing (NDT), various methods have been evaluated for their effectiveness, approaches, and outcomes, with each NDT method presenting distinct advantages and limitations influenced by pipeline conditions and defect types [20]. This comparative analysis is essential for selecting the most suitable NDT technique for specific pipeline scenarios, thereby enhancing the overall safety and integrity of hydrogen-blended systems.

Future research should focus on refining signal classification processes and exploring additional parameters to improve the predictive capabilities of existing methods. These endeavors are crucial for advancing the precision and reliability of defect detection technologies, ultimately facilitating the safe integration of hydrogen into energy systems [14]. By leveraging these methodological advancements and case studies, stakeholders can develop robust safety assessment frameworks that support the successful deployment of hydrogen infrastructure.

Method Name	Technological Integration	Data Management	Risk Assessment
IAEM[14]	Robotic Systems	Data Management Systems	Predictive Techniques
BBP[19]	Smart Sensors Deployed	Data Acquisition Method	-
PITDS[22]	-OTDR Technology	Acoustic Signals	Life Cycle

Table 1: Overview of technological integration, data management, and risk assessment methods employed in pipeline integrity management for hydrogen systems. The table summarizes the key methodologies, highlighting the integration of advanced technologies and strategic approaches to enhance pipeline reliability and cost-effectiveness.

5 Pipeline Integrity and Maintenance

5.1 Pipeline Integrity Management

Managing pipeline integrity in hydrogen systems involves leveraging advanced technologies and strategic methodologies to enhance both reliability and cost-effectiveness. A primary challenge is accurately evaluating defects using in-line inspection (ILI) data, crucial for predicting defect growth and optimizing maintenance strategies [13]. The integration of robotic technologies and sophisticated data management systems has revolutionized this field by enabling precise condition monitoring and timely interventions to prevent failures [20]. The acoustic emission method has emerged as a valuable tool, offering real-time insights for proactive maintenance [14].

Efficient data acquisition is also essential, particularly in harsh environments, with smart sensor networks demonstrating potential for reliable long-haul data transmission [19]. Incorporating life cycle cost analysis into decision support systems promotes a proactive approach to pipeline integrity, informed by a comprehensive understanding of current conditions and future risks [12]. Research methodologies include mechanical property tests, thermal stability tests, and life prediction techniques like tensile and DSC experiments [4]. These frameworks are crucial for evaluating materials and predicting long-term performance. Enhanced threat detection and classification accuracy can be achieved by incorporating feature-level contextual information and system combination strategies [22]. These methodologies significantly improve hydrogen pipeline integrity management, ensuring safe and efficient operations in the evolving energy landscape. Table 1 provides a comprehensive summary of the methods utilized in pipeline integrity management, emphasizing the role of technological integration, data management, and risk assessment in ensuring the reliability and safety of hydrogen systems.

5.2 Non-Destructive Testing (NDT) Methods

Non-destructive testing (NDT) methods are vital for assessing pipeline health and integrity, especially in hydrogen-integrated systems. These techniques enable inspection without causing damage, ensuring continuous operation and safety. Key NDT methods include magnetic flux leakage (MFL), ultrasonic testing (UT), electromagnetic acoustic technology (EMAT), and eddy current testing (EC) [20]. MFL is effective for detecting corrosion and metal loss, while UT offers high sensitivity for internal and surface defects. EMAT is suitable for high-temperature environments, and EC detects surface defects in conductive materials. These methods facilitate early threat detection and timely maintenance interventions. However, aging infrastructure and insufficient financial considerations often result in reactive practices that hinder effective maintenance [12]. Advanced methodologies like contextual feature extraction and decision combination enhance the classification performance of threat detection systems, improving NDT methods' accuracy and reliability [22]. These innovations ensure the safe operation of hydrogen-blended systems.

5.3 Innovative Acoustic Emission Method (IAEM)

The Innovative Acoustic Emission Method (IAEM) significantly advances pipeline integrity assessment in hydrogen-blended systems. By analyzing acoustic emission signals, IAEM identifies parameters associated with material failure stages [14]. This method provides continuous monitoring, capturing transient events that periodic inspections might miss, thereby enhancing pipeline quality and safety management [4, 13, 14, 20, 12]. Sensors deployed along pipelines capture emissions from stress-induced changes, with data analysis revealing degradation patterns. Integrating IAEM with ILI data strengthens pipeline integrity management, enhancing gas transportation systems' reliability and

safety [13, 20, 14]. The IAEM supports predictive maintenance frameworks, allowing operators to anticipate failures and mitigate catastrophic risks. Using sophisticated data analytics and acoustic emission analysis fosters timely inspections and maintenance, improving hydrogen-blended pipelines' safety and reliability while extending infrastructure lifespans.

5.4 Data Management and Monitoring Systems

Effective data management and monitoring systems are crucial for pipeline safety and integrity, particularly in hydrogen-blended systems. These systems offer real-time insights into pipeline conditions, facilitating informed maintenance and safety interventions. Smart sensor networks utilizing a bucket brigade-inspired method enhance data transmission, reducing contention and electromagnetic interference [19]. Advanced data management techniques, including life cycle cost analysis-based decision support systems and innovative NDT methods, address challenges posed by harsh environments. Traditional data transmission methods often fall short, increasing failure risks due to corrosion and degradation. Integrating advanced analytics and risk assessment enables proactive integrity management, minimizing unexpected downtime and maintenance costs [14, 13, 20, 12]. Combining data management systems with advanced monitoring technologies like NDT and IAEM creates a comprehensive safety framework. Real-time data acquisition with NDT techniques allows targeted maintenance interventions, reducing catastrophic failure risks [14, 20]. Effective data management that incorporates historical information is vital for condition-based maintenance strategies, enhancing safety and operational efficiency in energy transportation infrastructure [14, 13, 20]. Advanced technologies and innovative transmission methods improve monitoring capabilities, ensuring safe and efficient energy system operations during the transition to sustainable energy sources.

6 Renewable Gas Integration

6.1 Role of Hydrogen in Decarbonizing Energy Systems

Hydrogen plays a pivotal role in decarbonizing energy systems by integrating renewable energy sources and enhancing infrastructure sustainability. As an energy carrier, it mitigates renewable energy curtailment and enhances storage, improving energy supply reliability and stability, crucial for achieving net-zero targets. The coupling of electricity and hydrogen systems is essential for comprehensive decarbonization efforts [5].

Hydrogen-based hybrid microgrids demonstrate hydrogen's potential in energy management and system stability, significantly aiding decarbonization [12]. These systems use hydrogen as a backup energy source, enhancing performance and reliability while reducing fossil fuel reliance. Advanced optimization models for hydrogen infrastructure management highlight the feasibility of cost optimization and the transition to renewable energy.

In heavy-duty transportation, hydrogen fuel cells offer a promising solution for reducing greenhouse gas emissions and enhancing sustainability. National hydrogen economy roadmaps stress the need for investment in hydrogen production, storage, and infrastructure, especially for heavy-duty vehicles (HDVs) that benefit from hydrogen's high energy density. As focus shifts from light-duty vehicles to HDVs, advancements in polymer electrolyte membrane fuel cells are crucial to meet the specific efficiency and durability requirements of trucks, buses, locomotives, and marine vessels. By 2050, hydrogen could significantly meet global energy needs, particularly in transportation, driven by government support for transitioning away from internal combustion engines [10, 11, 7, 3]. Integrating green hydrogen into national energy frameworks has shown substantial cost reductions and provided sustainable alternatives to fossil fuels, particularly in hard-to-abate sectors.

Research underscores successful pathways for infrastructure transformation, highlighting hydrogen integration's feasibility in energy systems. Future research should explore innovative regulatory frameworks, such as zonal tariffs and non-price mechanisms, to enhance hydrogen integration into existing markets and address market dynamics complexities. Studies indicate that spatially differentiated electricity pricing can significantly reduce congestion costs and optimize hydrogen production locations, leading to lower end-use costs and improved efficiency in electricity and hydrogen supply chains. An integrated energy system framework that considers the interdependencies between hy-

hydrogen and electricity sectors can facilitate cost-effective investments and enhance decarbonization strategies' overall performance [2, 1, 5, 9, 8].

Hydrogen's multifaceted role in decarbonizing energy systems includes balancing seasonal variability in renewable sources, replacing fossil fuels in hard-to-abate sectors, and enhancing overall system cost-effectiveness. Technological advancements in hydrogen production and storage, alongside strategic infrastructure development—such as expanding pipelines and storage facilities—are critical for integrating hydrogen into electricity and industrial sectors. Regulatory innovations are also necessary to facilitate investments and coordinate the transition to a hydrogen-based economy, ensuring green hydrogen competes effectively with traditional fossil fuels while meeting climate and energy policy targets [1, 9]. By leveraging these elements, hydrogen can substantially contribute to the global transition toward sustainable and resilient energy systems.

6.2 Economic and Environmental Impacts

Integrating renewable gases, particularly hydrogen, into energy systems has significant economic and environmental impacts. Economically, hydrogen technologies, such as fuel cells in heavy-duty transportation, offer substantial cost savings and efficiency improvements. Advances in material technologies crucial for fuel cell implementation are essential for reducing production costs and enhancing hydrogen's economic viability as a fuel source [7]. These advancements improve fuel cell performance and durability while lowering operational costs in hydrogen-based systems.

Environmentally, hydrogen integration offers a pathway to significantly reduce carbon emissions, aiding climate change mitigation. As a clean energy carrier, hydrogen facilitates the decarbonization of sectors challenging to electrify directly. By decreasing reliance on fossil fuels and increasing renewable energy integration, hydrogen is pivotal in transitioning to a sustainable energy future. Multi-energy hybrid systems that combine renewable energies, batteries, and hydrogen address wind and solar power curtailment through efficient energy conversion and storage. Implementing hydrogen enhances energy efficiency and reliability within these systems and contributes to decarbonizing energy supply and industrial processes. Robust hydrogen infrastructure development is vital for meeting future energy demands and achieving climate neutrality goals by 2050 [1, 15].

Establishing hydrogen infrastructure is poised to significantly reduce energy-related environmental impacts by lowering greenhouse gas emissions and minimizing energy systems' carbon footprints. This is particularly pertinent in Great Britain, where prioritizing green hydrogen hubs can support decarbonization across heating, industry, and transport sectors. Utilizing advanced production technologies such as methane reformation with carbon capture, biomass gasification, and electrolysis can enable the deployment of up to 10 GW of hydrogen production capacity by 2050. In China, integrating hydrogen into electricity and hard-to-abate sectors has been shown to reduce the levelized cost of a zero-carbon electricity system by 17

The economic and environmental impacts of integrating renewable gases are significant, offering dual benefits of cost savings and environmental sustainability. By advancing hydrogen technologies and infrastructure, stakeholders can bolster the resilience and sustainability of the energy system, supporting global decarbonization goals. Establishing green hydrogen hubs to meet demands across heating, industry, and transport can facilitate the rollout of up to 10 GW of hydrogen production capacity by 2050. Moreover, integrating hydrogen infrastructure with electricity systems can lead to substantial cost savings—up to 17

6.3 Hydrogen Infrastructure and Energy Security

Hydrogen infrastructure is crucial for enhancing energy security by providing a versatile and reliable means of storing and distributing energy across various sectors. Strategically integrating hydrogen into energy systems facilitates energy source diversification and ensures a stable, resilient energy supply, especially amid fluctuating renewable energy outputs. The development of robust hydrogen infrastructure, supported by advanced optimization models, enables effective management of hydrogen flows and investments, thus promoting a secure and sustainable energy framework [5].

Coupling hydrogen infrastructure with existing energy systems offers significant energy security advantages. By utilizing hydrogen as an energy carrier, systems can accommodate renewable sources' variability, such as solar and wind, ensuring a continuous and reliable energy supply [16]. This

integration is particularly advantageous for regions aiming to reduce dependence on imported fossil fuels, enhancing energy independence and resilience.

Furthermore, deploying hydrogen infrastructure supports energy system decarbonization, contributing to energy security by lowering greenhouse gas emissions and mitigating climate change impacts. Strategic planning and optimization of hydrogen infrastructure, including developing storage and distribution networks, are crucial for meeting future energy demands and achieving climate neutrality targets [1].

7 Challenges and Future Directions

7.1 Economic and Material Challenges

The incorporation of hydrogen into urban gas pipelines presents notable economic and material challenges critical to the adoption of hydrogen-blended systems. Significant initial investments in hydrogen production and storage technologies pose economic barriers, hindering the advancement of hydrogen-based hybrid microgrid systems [6]. This challenge is further exacerbated by the need for substantial improvements in fuel cell materials and designs to fulfill the operational demands of heavy-duty applications [7].

Material degradation and the underdevelopment of hydrogen infrastructure complicate the commercialization of fuel cells [10]. Managing hybrid systems to optimize performance and minimize costs necessitates sophisticated modeling and resource allocation strategies [16]. The reliance on underground hydrogen storage, particularly insufficient in regions like China, highlights a critical infrastructural limitation impacting hydrogen integration viability [9].

The lack of open-source models for hydrogen infrastructure development is a significant barrier, indicating the need for innovative strategies to address these economic and material challenges [5]. Moreover, existing models often neglect last-mile distribution networks, adversely affecting overall hydrogen supply chain dynamics [8].

Pipeline integrity issues, coupled with limitations in current non-destructive testing (NDT) methods and complex pipeline environments, necessitate robust data management systems for informed maintenance decisions [20]. Simple and robust data communication protocols, such as the bucket brigade-inspired method, offer effective solutions for data management without complex routing mechanisms [19].

Future research should focus on refining models to incorporate detailed market dynamics, enhancing spatial and temporal resolutions, and exploring alternative hydrogen storage methods [1]. The development of multi-energy hybrid systems may improve energy efficiency and reduce reliance on external power sources, addressing economic and material challenges in hydrogen-blended systems [15]. Overcoming these challenges is crucial for successfully integrating hydrogen into urban gas pipelines, ensuring the viability and sustainability of hydrogen-blended energy systems.

7.2 Policy and Regulatory Frameworks

Advancing hydrogen infrastructure and integrating hydrogen into existing energy systems require effective policy and regulatory frameworks. These frameworks are essential for addressing the technical and economic challenges of hydrogen technologies, such as fuel cells, while promoting public awareness of their safety and benefits [10]. Public sensitization is vital for societal acceptance and the successful deployment of hydrogen technologies.

In heavy-duty transportation, policy initiatives are crucial for supporting the transition to hydrogen-powered systems by incentivizing infrastructure development and fostering investment in research and development [7]. Regulatory support can drive innovation in hydrogen technologies, facilitating the commercialization of fuel cells and addressing technical issues hindering widespread adoption [11].

The exploration of heterogeneous hydrogen demands across sectors requires comprehensive regulatory frameworks that consider sector-specific requirements and logistics, including last-mile distribution [8]. These frameworks should harmonize standards and protocols, ensuring compatibility and interoperability throughout the hydrogen supply chain.

Future research should enhance data analytics for defect prediction and develop hybrid inspection methods to improve pipeline monitoring and maintenance. Automated solutions for continuous monitoring can further strengthen regulatory compliance and safety standards in hydrogen infrastructure [20].

Robust policy and regulatory frameworks are critical for effectively integrating hydrogen into energy systems, addressing barriers, promoting technological innovation, and facilitating a sustainable energy transition. These frameworks must support developing comprehensive hydrogen infrastructure, including expanding storage and pipeline networks, while aligning hydrogen production technologies with sector-specific demands. Strategic planning and investment in domestic production and import capabilities are essential to meet future energy targets and ensure the cost-competitiveness of green hydrogen, particularly in decarbonizing critical sectors like electricity generation and heavy industry [9, 1, 5]. Addressing these challenges will facilitate the widespread adoption of hydrogen technologies and support the global transition to cleaner energy systems.

8 Conclusion

The integration of hydrogen into urban gas pipelines represents a pivotal advancement in the pursuit of sustainable energy systems. As a versatile energy carrier, hydrogen offers substantial environmental benefits, including the reduction of carbon emissions and the enhancement of energy security. The transition to hydrogen-blended fuels, however, necessitates addressing several technical and economic hurdles, such as the high costs associated with hydrogen production and storage, and the development of advanced materials to ensure pipeline integrity. Implementing a comprehensive technical framework for the detection and assessment of pipeline integrity, particularly for systems utilizing polyethylene pipes, is crucial for the safe incorporation of hydrogen into existing infrastructures. This framework not only supports pipeline integrity but also facilitates the secure integration of hydrogen, underscoring the importance of ongoing research and collaborative efforts. The refinement of policy and regulatory measures is vital to fostering infrastructure development and technological progress. A coordinated strategy that involves diverse stakeholders is essential to drive innovation and ensure a seamless transition to hydrogen-enhanced energy systems. By overcoming these challenges and leveraging hydrogen's potential, urban gas pipelines can play a significant role in the global transition towards cleaner and more resilient energy solutions.

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