BLENDING HYDROGEN WITH NATURAL GAS IN DISTRIBUTION NETWORKS: TECHNICAL AND SAFETY CONSIDERATIONS

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This review presents a comprehensive assessment of hydrogen blending into natural gas (NG) networks as a transitional strategy to support the decarbonization of energy systems. The review addresses key technical, environmental, and operational aspects of hydrogen-enriched natural gas (HENG). It covers the motivation for hydrogen blending, the role of hydrogen in managing renewable energy intermittency, its impact on gas grid dynamics, flammability and explosion behavior, leakage and safety concerns, and end-use appliance compatibility. The findings confirm that hydrogen blending up to 20 % is technically feasible and can reduce greenhouse gas emissions while using existing infrastructure. However, success depends on updated standards, advanced monitoring technologies, and coordinated regulatory frameworks. The review concludes with a synthesis of knowledge gaps and recommendations for future research and deployment.

Key words: hydrogen; natural gas; fire safety; feasibility

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1. Introduction

The decarbonization of the energy system is a central objective in achieving global climate targets outlined in international frameworks such as the Paris Agreement. One promising pathway toward this goal is the integration of hydrogen (H_2) into existing natural gas (NG) infrastructure. Hydrogen, particularly when produced via electrolysis using renewable electricity (green hydrogen), represents a carbon-neutral energy carrier that can displace part of the fossil-based NG, thereby reducing greenhouse gas (GHG) emissions without immediate infrastructure overhauls.

Hydrogen blending into NG networks offers a transitional solution that supports both decarbonization and energy system flexibility. According to the International Energy Agency, blending up to 20 % H_2 by volume into the European gas grid could avoid over 150 million tonnes of CO_2 annually [1]. Several national pilot projects—including GRHYD in France [2], WindGas Haßfurt in Germany [3], and efforts in Tunisia [4] and South Korea [5] demonstrate the viability of hydrogen injection into distribution systems.

In these and similar studies [6–8], researchers evaluated technical and regulatory frameworks for hydrogen injection, showing that moderate blending levels (up to 20 %) do not significantly compromise gas quality or safety. Nevertheless, further work is needed to address challenges related to gas appliance compatibility, pipeline material degradation, combustion performance, and measurement technologies. These challenges form the thematic foundation of this review, which synthesizes findings from over 30 peer-reviewed articles, pilot trials, and simulation studies.

In the following sections, we examine the motivation for hydrogen blending in relation to decarbonization goals, explore hydrogen's role in balancing variable renewable energy (VRE), assess the physical effects of hydrogen injection, evaluate flammability and explosion risks, analyze leak and material integrity issues, and discuss implications for end-use appliances and broader system integration.

2. Hydrogen as a Decarbonization Vector in the Gas Grid

The replacement of fossil-based natural gas with hydrogen is a critical strategy for achieving deep decarbonization of the energy sector. Combustion of hydrogen produces no direct CO_2 emissions, only water vapor, which makes it highly attractive in climate policy frameworks. The integration of hydrogen into gas grids is especially appealing due to the potential use of existing infrastructure, which reduces the need for high capital expenditures associated with dedicated hydrogen pipelines.

The greenhouse gas mitigation potential of hydrogen blending has been evaluated in multiple techno-economic studies. For instance, Paglini et al. [9] quantified the reduction in greenhouse gas emissions associated with hydrogen-natural gas mixtures, showing that even partial substitution of NG with H_2 significantly lowers both CO_2 and CH_4 emissions on a lifecycle basis. Similarly, Ren et al. [10] modeled dynamic leakage and dispersion behavior and concluded that effective blending can provide environmental benefits while also mitigating risks.

Environmental co-benefits are further discussed by Khatiwada et al. [1], who assessed hydrogen integration in the Portuguese gas network. They found that replacing 20 % of NG with green hydrogen could reduce annual CO_2 emissions by over 1.5 Mt, assuming average residential and industrial gas demand. However, the study also emphasized systemic challenges such as high electrolysis costs, grid constraints, and the need for policy alignment.

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Another aspect of hydrogen's decarbonization role relates to the carbon intensity of hydrogen itself. Green hydrogen has nearly zero emissions, while blue hydrogen (produced via methane reforming with carbon capture) has a variable footprint depending on capture efficiency and upstream leakage. Multiple studies [11–13] compare these pathways and suggest prioritizing green hydrogen where renewable electricity is abundant.

Blending also provides a practical way to scale up hydrogen production gradually. By using hydrogen as an additive, infrastructure operators can gain operational experience, evaluate regulatory implications, and prepare consumers and equipment manufacturers for a potential long-term transition to 100 % hydrogen systems.

3. Hydrogen Blending as a Solution to Renewable Energy Intermittency

A major challenge in energy systems dominated by renewable energy sources (RES) is their intermittency. Solar and wind generation are inherently variable and non-dispatchable, often leading to significant mismatches between supply and demand. Hydrogen offers a promising energy storage solution through Power-to-Gas (P2G) technology, whereby excess electricity from RES is used to produce hydrogen via electrolysis, which can then be stored and injected into the natural gas grid.

In the WindGas Haßfurt pilot project in Germany [3], a proton exchange membrane (PEM) electrolyzer with a 1.25 MW capacity was used to convert excess wind power into hydrogen. This hydrogen was then blended into the local gas distribution network at concentrations of up to 10 % by volume. The project demonstrated not only the technical feasibility of the P2G concept but also its effectiveness in supporting grid stability during periods of excess renewable electricity production.

Similarly, the GRHYD project in Dunkirk, France, implemented a P2G demonstration that supplied approximately 200 households with hydrogen-enriched natural gas, maintaining a blend of up to 20 % H_2 [2]. Monitoring data from the project indicated that gas appliances performed within normal parameters, and no significant safety or efficiency issues were reported. The project was instrumental in informing regulatory frameworks and assessing public acceptance.

GasNet has initiated a pilot project for low percentages hydrogen blending into its natural gas network in Hranice u Aše, [14] to provide practical data on operational performance, material compatibility, and potential safety implications and to assess the feasibility of integrating renewable hydrogen into existing gas networks.

Yang et al. [15] developed a hybrid model for evaluating risks in integrated power-gas systems, including hydrogen blending scenarios. Their simulations showed that hydrogen injection at concentrations up to 5 % and at pipeline pressures below 7 MPa does not pose significant operational risks. These findings align with other modeling studies that consider blending as a method of RES integration and grid flexibility enhancement [15,16].

In Tunisia, Bdioui et al. [4] proposed the use of hydrogen blending to address the variability of solar power in the national energy mix. Their simulations considered technical constraints of the existing distribution network and suggested that up to 15 % hydrogen blending could be achieved without compromising safety or service quality. The study underlined the role of hydrogen not just as a decarbonization vector, but also as a means to increase the share of renewables in final energy consumption.

From an economic standpoint, Ramsebner et al. [17] conducted a cost-benefit analysis of hydrogen injection and found that the value of avoided renewable curtailment and reduced CO_2 emissions can outweigh the capital cost of electrolyzer installation under favorable electricity price scenarios. Additionally, hydrogen blending allows for better utilization of curtailed renewable electricity, helping to stabilize markets and incentivize investment in green hydrogen production capacity.

The consensus across studies [2–4], [14–17] is that hydrogen blending can serve as a flexible, scalable, and technically feasible approach to managing renewable intermittency. However, challenges remain regarding electrolyzer efficiency, regulatory harmonization, and the development of dynamic gas quality monitoring systems to ensure compatibility across the gas infrastructure.

4. Injection and Mixing of Hydrogen into the Gas Grid

The introduction of hydrogen into natural gas (NG) distribution systems substantially modifies flow characteristics, pressure regimes, and gas quality parameters. Due to its lower molecular mass, higher diffusivity, and lower density compared to methane, hydrogen affects gas dynamics in both steady-state and transient conditions.

Li et al. [18] employed a transient gas flow model to simulate hydrogen injection at a single point into a branched low-pressure distribution network. Their simulations demonstrated concentration fluctuations and pressure deviations and transient effects localized primarily downstream from the injection point, with the magnitude of deviation directly proportional to the hydrogen concentration. Notably, hydrogen propagation caused increased flow velocities and localized pressure drops that must be accounted for in pipeline design and pressure regulation settings.

Chae et al. [5] assessed hydrogen injection in polyethylene (PE) pipeline networks using empirical field data from South Korea. They concluded that hydrogen concentrations up to 10 vol % could be integrated without exceeding the mechanical stress limits of standard PE100-RC materials. However, real-time monitoring of gas composition and pressure was recommended to avoid deviations outside design tolerances, particularly under variable demand scenarios.

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Cheli et al. [6] utilized computational fluid dynamics (CFD) simulations to model the spatial dispersion of hydrogen within complex branched distribution networks under varying demand conditions. Their results highlighted the formation of hydrogen-enriched pockets due to differential flow rates and mixing inefficiencies, emphasizing the need for dynamic gas quality monitoring technologies capable of detecting localized anomalies in hydrogen concentration.

Field experiments reported by Jaworski et al. [19] confirmed that conventional pressure regulators and valves maintained functionality under hydrogen-enriched conditions (up to 10 vol. % H_2) without mechanical failure or leakage. Nevertheless, calorific value fluctuations were observed, suggesting that billing and metering systems require recalibration to maintain measurement accuracy in the presence of hydrogen.

Gong et al. [20] applied artificial neural network (ANN) modeling to predict hydrogen dispersion and accumulation in confined pipeline sections. Their results demonstrated that dispersion patterns depend sensitively on pipe diameter, surface roughness, flow velocity, and hydrogen injection rates, underlining the need for predictive computational tools in network design and operation.

Collectively, the findings from studies [5,6,18–20] demonstrate that while hydrogen injection into NG distribution grids is technically feasible, successful implementation requires comprehensive adjustments in network monitoring, flow control strategies, and gas quality assurance protocols. Network-specific assessments must consider topology, pipeline material, pressure class, and local demand variability to optimize operational safety and gas delivery performance.

5. Impact on Flammability and Explosion Parameters

The admixture of hydrogen into natural gas significantly alters the combustion and explosion characteristics of the resulting gas mixture. Due to hydrogen's broader flammability range (4–75 vol. % in air), higher laminar burning velocity (approximately 2.65 m/s compared to 0.43 m/s for methane), lower minimum ignition energy (0.02 mJ), and lower ignition temperature, hydrogen-enriched natural gas (HENG) exhibits distinct combustion behavior compared[15 to conventional natural gas.

Mitu et al. [21] conducted controlled laboratory experiments using the heat flux method to measure the laminar burning velocity (LBV) of CH_4/H_2/air mixtures across varying hydrogen volume fractions. Their results demonstrated a near-linear increase in LBV with increasing hydrogen concentration, with velocities exceeding 120 cm/s at 40 % hydrogen. The elevated LBV has direct implications for burner stability, flashback risk, and flame control strategies in end-use combustion systems.

Wojtowicz et al. [22] examined explosion parameters of HENG mixtures under confined vessel conditions. Their work quantified the relationship between hydrogen fraction and key explosion metrics, showing that maximum explosion pressure and rate of pressure rise increased significantly with hydrogen content. For instance, a 30 vol. % hydrogen blend yielded a maximum explosion pressure of 8.5 bar compared to 7.2 bar for pure methane. The time to peak pressure was also shortened, increasing the severity of explosion events.

Gong et al. [20] developed a predictive model using a genetic algorithm–optimized backpropagation (GA-BP) neural network to simulate gas accumulation and explosion behavior in underground technical corridors. The model incorporated environmental parameters such as ventilation rates, ambient temperature, and crack geometry. Simulations revealed that hydrogen-enriched mixtures accumulated preferentially near the ceiling and that the explosive volume increased substantially with hydrogen content and decreasing ventilation effectiveness.

Yang et al. [14] utilized dynamic leakage modeling to assess the flammability hazard associated with small hydrogen leaks. Their results emphasized that hydrogen's high diffusivity and low density lead to rapid formation of flammable zones, even in moderately ventilated areas, necessitating enhanced sensor deployment and ventilation design in risk-prone environments.

Cristello et al. [8] implemented adaptive neuro-fuzzy inference systems (ANFIS) for leak detection, achieving high accuracy in distinguishing leak events involving hydrogen-enriched gases. Their work underscores the critical role of real-time detection in mitigating explosion hazards associated with HENG.

The cumulative findings from these studies [8,14,20–22] highlight that even moderate levels of hydrogen blending significantly modify flammability limits, flame propagation dynamics, and explosion severity. This necessitates the revision of existing design standards for combustion devices, ventilation systems, explosion venting, and gas detection technologies to ensure safe operation under HENG conditions.

6. Leakages, Gas Discharge, and Operational Safety Considerations

Hydrogen's distinct physical properties—specifically its small molecular size, high diffusivity, and low viscosity—substantially influence leakage behavior, material compatibility, and operational safety in hydrogen-enriched natural gas (HENG) networks. These characteristics necessitate revised methodologies for integrity assessment, leak detection, and maintenance protocols.

Li et al. [6] reviewed hydrogen-induced degradation phenomena in metallic pipeline materials. Their study confirmed that hydrogen adsorption and subsequent diffusion into high-strength steels promote hydrogen-induced cracking (HIC) and reduction in fracture toughness, particularly at weld seams and material discontinuities. This necessitates the reevaluation of material selection criteria and the adoption of hydrogen-compatible steels or surface treatments to mitigate embrittlement.

Milenin et al. [23] performed a detailed numerical analysis of brittle fracture initiation and propagation in

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welded joints exposed to hydrogen environments. Their simulations highlighted that even minimal hydrogen ingress significantly lowers the critical stress intensity factor (K_IC), indicating increased susceptibility to sudden failure under operational loads.

Non-metallic sealing materials were evaluated by Liang et al. [7] for hydrogen permeability and structural integrity under cyclic pressure conditions. Elastomers such as EPDM, FKM, and NBR demonstrated varying degrees of hydrogen permeation, with EPDM exhibiting the highest permeability. These findings underscore the need to revise material specifications for gaskets, O-rings, and valve seats in HENG applications.

Ren et al. [10] utilized computational fluid dynamics (CFD) to simulate dynamic leakage scenarios in residential pipeline networks. Their findings indicated that hydrogen leakage rates are significantly higher than methane leakage rates under equivalent defect conditions, necessitating enhanced leak detection sensitivity and more frequent inspection intervals.

Jones et al. [19] conducted field testing of standard residential diaphragm gas meters under 10–20 % hydrogen blends. The results showed no catastrophic failures, but slight calibration drifts were observed, primarily due to hydrogen's lower density and faster response to pressure changes. The authors recommended recalibration protocols and the development of hydrogen-specific metrology standards.

Yang et al. [14] modeled hydrogen accumulation in confined building spaces and concluded that due to hydrogen's low density, stratification near ceilings occurs rapidly. Concentrations exceeding the lower flammability limit (LFL) can form within minutes, particularly under low-ventilation scenarios. This emphasizes the necessity for ceiling-mounted hydrogen-specific gas detectors and targeted ventilation design enhancements.

Cristello et al. [8] proposed adaptive neuro-fuzzy inference systems (ANFIS) for the real-time detection and classification of hydrogen leaks based on pressure transient analysis. Their system achieved high classification accuracy, offering a viable solution for early leak identification and risk mitigation.

Collectively, these studies [6–8,10,14,19,23] demonstrate that hydrogen blending significantly elevates leakage and material degradation risks relative to pure methane systems. Successful deployment of HENG therefore requires not only material upgrades and revised sensor placement but also the adoption of predictive maintenance strategies based on real-time monitoring and advanced modeling tools.

7. End-Use Appliances and Energy System Integration

The integration of hydrogen-enriched natural gas (HENG) into existing distribution networks necessitates a rigorous evaluation of the performance, durability, and safety of end-use appliances. Variations in the combustion properties of the fuel blend—such as reduced volumetric energy density, increased flame speed, and broadened flammability limits—can affect the operational behavior and emission characteristics of residential, commercial, and industrial gas-consuming devices.

The THyGA project [10] systematically tested 160 gas appliances, including condensing boilers, water heaters, and cooktops, to assess their performance under hydrogen blending up to 30 vol. %. The findings revealed that approximately 80 % of the tested appliances maintained compliant operation with hydrogen concentrations up to 20 vol. %, although minor adjustments to burner settings and air-fuel mixing ratios were sometimes necessary. Appliances exhibiting partial non-compliance (approximately 15 %) predominantly faced issues such as flashback, ignition delay, or elevated NO_x emissions.

Jaworski et al. [24,25] conducted detailed operational tests on residential gas meters and heating appliances exposed to hydrogen blends. Their study demonstrated that standard diaphragm meters could maintain measurement accuracy within regulatory tolerances up to 20 % hydrogen admixture, though shifts in flow measurement linearity were observed at very low and very high flow rates. Moreover, appliance durability under cyclic thermal and pressure loads was evaluated, revealing minor degradation of sealing components over prolonged exposure.

Wojtowicz et al. [22] performed combustion trials on domestic condensing boilers and determined that hydrogen-enriched mixtures increased the flame temperature, resulting in higher NO_x emissions. However, appropriate modulation of primary air supply and burner head geometry effectively mitigated these effects, preserving appliance efficiency and emission compliance.

Cuoci et al. [26] utilized computational fluid dynamics (CFD) simulations to investigate the combustion behavior of hydrogen-enriched methane in domestic boiler burners. Their results confirmed that traditional burner designs optimized for pure methane exhibit suboptimal mixing and higher susceptibility to flashback under HENG conditions. They proposed burner modifications, including staged combustion and optimized perforation patterns, to enhance stability and reduce pollutant formation.

Glanville et al. [27] assessed the long-term operational integrity of residential appliances under hydrogen-enriched conditions. Their study indicated that elastomeric materials used in seals and gaskets may undergo accelerated aging when exposed to hydrogen, necessitating the development of hydrogen-tolerant materials for critical components.

Leicher et al. [28] expanded the evaluation to include user comfort aspects such as ignition behavior, operational noise, and thermal performance. They observed that ignition timing and burner startup dynamics were affected by the lower ignition energy and higher flame speed of hydrogen-containing mixtures, prompting recommendations for adaptive ignition system designs.

Collectively, these findings [10,22,25–28] indicate that while the majority of current appliances can accommodate moderate hydrogen admixtures with minimal modifications, comprehensive standards for "hydrogen-ready" certification are essential to ensure safe, efficient, and durable appliance operation. Future integration strategies must include rigorous testing protocols, adaptive design practices, and the development of materials and components explicitly optimized for hydrogen-rich environments.

8. Conclusions

This review has comprehensively evaluated the technical, combustion-related, safety, material, and appliance integration aspects of hydrogen blending into natural gas networks. Based on the synthesis of experimental data, numerical modeling, and pilot project experiences, several critical conclusions can be drawn:

- Blending hydrogen up to 20 vol. % into low- and medium-pressure natural gas distribution systems is technically feasible without substantial retrofitting, particularly in polyethylene (PE) networks.
- Hydrogen's distinct physical properties necessitate modifications in gas quality monitoring, leakage detection, and material compatibility standards. Hydrogen permeation, embrittlement, and accelerated aging of non-metallic components must be systematically addressed.
- The presence of hydrogen significantly alters flammability limits, ignition characteristics, and explosion dynamics, requiring reassessment of explosion protection systems, ventilation strategies, and combustion control technologies.
- Residential and commercial appliances can generally tolerate hydrogen blends up to 20 vol. % with minimal performance degradation; however, targeted burner optimizations, recalibration of metering devices, and the development of hydrogen-tolerant components are necessary to maintain operational safety and efficiency.
- Power-to-Gas systems that inject hydrogen into the grid provide an effective mechanism for absorbing excess renewable electricity, thus contributing to system flexibility and decarbonization.

Future work should prioritize long-term material degradation studies under cyclic operational stresses, large-scale validation of leak detection systems, harmonization of international gas quality standards for hydrogen blends, and development of certification protocols for hydrogen-ready appliances.

Hydrogen blending represents a technically robust and scalable pathway to support decarbonization goals while leveraging existing energy infrastructure. Its successful deployment, however, will require interdisciplinary collaboration among engineers, material scientists, policymakers, and appliance manufacturers, as well as comprehensive risk assessment frameworks and adaptive regulatory mechanisms.

9. References

1. Khatiwada D. et al., Decarbonization of natural gas systems in the EU e costs, barriers, and constraints of hydrogen production with a case study in Portugal. Renew Sustain Energy Rev 2022;168:112775. https://doi.org/10.1016/j.rser.2022.112775.
2. Alliat I.: GRHYD : a successfull demonstration for the new gas H2NG, 8th HIPS-Net workshop, June 17, 2021. https://www.dbi-gruppe.de/wp-content/uploads/2023/08/HIPS-NET-WS-2021_ENGIE_GRHYD_Alliat.pdf
3. Uniper Energy Storage GmbH. (2017). Review of the Uniper Energy Storage GmbH Power-To-Gas Facility in Falkenhagen. EPRI – Product 3002011519. Available at: https://rest-service.epri.com/publicdownload/000000003002011519/0/Product
4. Bdioui, H., Touati, H., Ben Chiekh, M., López-Agüera, A., 2024. Green Hydrogen Blending into the Tunisian Natural Gas Distributing System. Hydrogen 5, 1004–1019. https://doi.org/10.3390/hydrogen5040054
5. Chae, M.J., Kim, J.H., Moon, B., Park, S., Lee, Y.S., 2022. The present condition and outlook for hydrogen-natural gas blending technology. Korean Journal of Chemical Engineering 39, 251–262. https://doi.org/10.1007/s11814-021-0960-8
6. Cheli, L., Guzzo, G., Adolfo, D., Carcasci, C., 2021. Steady-state analysis of a natural gas distribution network with hydrogen injection to absorb excess renewable electricity. International Journal of Hydrogen Energy 46, 25562–25577. https://doi.org/10.1016/j.ijhydene.2021.05.100
7. Liang, X., Fei, F., Ma, W., Wang, K., Ren, J., Yao, J., 2024. Study on Suitability Evaluation Method of Non-Metallic Seals in Long Distance Hydrogen-Doped Natural Gas Pipelines. Processes 12, 2353. https://doi.org/10.3390/pr12112353
8. Cristello, J.B., Dang, Z., Hugo, R., Park, S.S., 2024. Artificial intelligence based leak detection in blended hydrogen and natural gas pipelines. International Journal of Hydrogen Energy 91, 744–764. https://doi.org/10.1016/j.ijhydene.2024.10.146
9. Paglini, R., Minuto, F.D., Lanzini, A., 2024. Estimating Greenhouse Gas Emissions from Hydrogen-Blended Natural Gas Networks. Energies 17, 6369. https://doi.org/10.3390/en17246369
10. Leicher, J., Schaffert, J., Cigarida, H., Tali, E., Burmeister, F., Giese, A., Albus, R., Görner, K., Carpentier, S., Milin, P., Schweitzer, J., 2022. The Impact of Hydrogen Admixture into Natural Gas on Residential and Commercial Gas Appliances. Energies 15, 777. https://doi.org/10.3390/en15030777
11. International Energy Agency (IEA), "Global hydrogen review," 2023. Available at: https://www.iea.org/reports/global-hydrogen-review-2024
12. Arya, A.K., Katiyar, R., Kumar, P.S., Kapoor, A., Pal, D.B., Rangasamy, G., 2023. A multi-objective

model for optimizing hydrogen injected-high pressure natural gas pipeline networks. International Journal of Hydrogen Energy 48, 29699–29723. https://doi.org/10.1016/j.ijhydene.2023.04.133
13. Zhang, C., Shao, Y., Shen, W., Li, H., Nan, Z., Dong, M., Bian, J., Cao, X., 2023. Key Technologies of Pure Hydrogen and Hydrogen-Mixed Natural Gas Pipeline Transportation. ACS Omega 8, 19212–19222. https://doi.org/10.1021/acsomega.3c01131
14. GasNet. Zpráva o udržitelnosti 2023. Available from: https://www.gasnet.cz/-/media/GasNet/Files/Gasnet/esg/GasNet_Zprava_o_udrzitelnosti_2023.pdf (in Czech)
15. Yang, K., Zhao, Z., Zhang, A., Yang, W., Li, Q., Zeng, S., Peng, G., 2024. Risk modelling of hydrogen-enriched natural gas on pipelines and gas-electric coupled systems. IET Energy Systems Integration 6, 253–267. https://doi.org/10.1049/esi2.12124
16. Islam, M. A., Alam, T., et al., Hydrogen blending in natural gas pipelines: A comprehensive review, International Journal of Hydrogen Energy, 2024. https://doi.org/10.1016/j.ijhydene.2024.10.384
17. Ramsebner J., Linares P., Hiesl A., Haas R.:Techno-economic evaluation of renewable hydrogen generation strategies for the industrial sector, International Journal of Hydrogen Energy, Vol. 60, 2024, 1020-1040, https://doi.org/10.1016/j.ijhydene.2024.02.167.
18. Li, T.; Xiao, J.; Zhang, H.; Cheng, J.; Li, K.; Wang, Y.; Lin, Y. Numerical Simulation Study of Gas Stratification in Hydrogen-Enriched Natural Gas Pipelines. Energies 2025, 18, 3181. https://doi.org/10.3390/en18123181
19. Jaworski, J.; Dudek, A. Study of the Effects of Changes in Gas Composition as Well as Ambient and Gas Temperature on Errors of Indications of Thermal Gas Meters. Energies 2020, 13, 5428. https://doi.org/10.3390/en13205428
20. Gong, X., Li, H., Li, C., Kou, M., Kong, L., Liu, H., 2025. Research on leakage and diffusion behavior of hydrogen doped natural gas in integrated pipeline corridors based on data drive. Scientific Reports 15, 786. https://doi.org/10.1038/s41598-024-51152-x
21. Mitu, M., Razus, D., Schroeder, V., 2021. Laminar Burning Velocities of Hydrogen-Blended Methane–Air and Natural Gas–Air Mixtures, Calculated from the Early Stage of p(t) Records in a Spherical Vessel. Energies 14, 7556. https://doi.org/10.3390/en14227556
22. Wojtowicz, R., 2019. An analysis of the effects of hydrogen addition to natural gas on the work of gas appliances. Nafta-Gaz 75, 465–473. https://doi.org/10.18668/ng.2019.08.03
23. Milenin, A., Velikoivanenko, E., Rozynka, G., Pivtorak, N., 2023. Numerical analysis of the brittle strength of welded pipelines with corrosion metal loss in the transportation of blends of natural gas with hydrogen. Welding in the World 67, 2803–2809. https://doi.org/10.1007/s40194-023-01612-5
24. Jaworski, J., Kułaga, P., Blacharski, T., 2020. Study of the Effect of Addition of Hydrogen to Natural Gas on Diaphragm Gas Meters. Energies 13, 3006. https://doi.org/10.3390/en13113006
25. Jaworski, J., Kułaga, P., Ficco, G., Dell'Isola, M., 2021. Domestic Gas Meter Durability in Hydrogen and Natural Gas Mixtures. Energies 14, 7555. https://doi.org/10.3390/en14227555
26. Cuoci, A., Bucci, G., Sutti, M., Faravelli, T., Frassoldati, A., 2024. Experimental and numerical study of pollutant emissions from a domestic condensing boiler fed with natural gas enriched with H2. Proceedings of the Combustion Institute 40. https://doi.org/10.1016/j.proci.2024.105473
27. Glanville, P., Fridlyand, A., Sutherland, B., Liszka, M., Zhao, Y., Bingham, L., Jorgensen, K., 2022. Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance. Energies 15, 1706. https://doi.org/10.3390/en15051706
28. Leicher, J., Schaffert, J., Cigarida, H., Tali, E., Burmeister, F., Giese, A., Albus, R., Görner, K., Carpentier, S., Milin, P., Schweitzer, J., 2022. The Impact of Hydrogen Admixture into Natural Gas on Residential and Commercial Gas Appliances. Energies 15, 777. https://doi.org/10.3390/en15030777