

Research Article

Experimental Investigation of Green Hydrogen Integration into Industrial Thermal Systems for Sustainable and Low Carbon Manufacturing Applications

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Abstract: Background: The global energy transition requires low-carbon solutions that can be integrated into existing thermal systems without drastic infrastructure changes. Hydrogen blending in conventional combustion systems has emerged as a promising pathway to reduce carbon emissions while maintaining operational flexibility. Objective: This study aims to experimentally evaluate the effect of hydrogen blending ratios (0–100% by volume) on thermal efficiency, CO₂ emissions, and NO_x emissions, and to determine the optimal blending range based on technical and economic feasibility. Methods: An experimental thermal system prototype was developed and tested under controlled conditions with three repetitions per operating point. Performance parameters included combustion temperature, fuel consumption rate, and thermal efficiency, while emissions of CO₂ and NO_x were measured using a calibrated gas analyzer. Data were analyzed using descriptive statistics, one-way ANOVA at a 0.05 significance level, confidence interval estimation, and linear regression to examine the relationship between hydrogen fraction and emission reduction. Results: The findings indicate that increasing hydrogen fraction significantly improves thermal efficiency, reaching 87.5% at 100% hydrogen, while CO₂ emissions decrease linearly to zero. However, NO_x emissions increase with higher hydrogen content due to elevated combustion temperatures. Statistical analysis confirms that hydrogen ratio has a significant effect on efficiency and emissions, with a strong linear correlation between hydrogen fraction and CO₂ reduction. A blending range of 40–60% hydrogen provides the most balanced performance in terms of efficiency improvement, emission reduction, and cost feasibility.

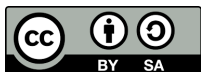
Received: February, 25 2024

Revised: March, 22 2024

Accepted: April, 29 2024

Published: May, 31 2024

Curr. Ver.: May, 31 2024



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Keywords: CO₂ Emissions; Combustion System Optimization; Hydrogen Blending; NO_x Emissions; Thermal Efficiency.

1. Introduction

Decarbonization of industrial thermal systems has become a central priority in global climate mitigation efforts. Industrial activities account for a significant proportion of global greenhouse gas (GHG) emissions, primarily due to the extensive use of fossil fuels for process heat generation. High-temperature operations in sectors such as cement, steel, chemicals, and petrochemicals rely heavily on coal, oil, and natural gas combustion, resulting in substantial carbon dioxide (CO₂) emissions and associated environmental impacts. A critical and systematic review by J. Chen et al. (2024) emphasizes that industrial heat demand represents one of the most challenging segments to decarbonize because of its continuous operation and high energy intensity. Similarly, techno-economic assessments indicate that without transformative interventions, fossil-intensive industrial systems will struggle to achieve deep decarbonization targets (Cormos et al., 2020).

Beyond climate change, fossil fuel dependency in industrial thermal systems contributes to broader environmental concerns, including air pollution and long-term resource depletion. The finite nature of fossil reserves raises sustainability and energy security concerns, particularly in the context of increasing global energy demand (Alipour et al., 2024). As industrial production expands to meet economic growth, the need for reliable and stable heat supply further complicates the transition toward low-carbon alternatives. Carbon-neutral heat strategies such as electrification, renewable-based heating, and thermal energy optimization have therefore gained attention as integral pathways to reducing emissions while maintaining industrial competitiveness (Y.-Y. Chen et al., 2024).

Carbon capture technologies constitute another major approach to mitigating emissions from fossil-based industrial processes. Reactive absorption and adsorption systems, including advanced solvent-based and looping technologies, demonstrate significant potential in reducing CO₂ emissions from large-scale industrial operations (Cormos et al., 2020). However, the large-scale deployment of these systems remains constrained by economic feasibility, infrastructure requirements, and operational integration challenges. The need for substantial capital investment, combined with uncertainties regarding long-term performance and regulatory support, has slowed widespread implementation.

Economic viability represents a critical barrier in the decarbonization transition. The global manufacturing sector is deeply embedded within fossil fuel-based supply chains, and transitioning to alternative energy systems entails considerable financial risks and structural adjustments. Alipour et al. (2024) argue that geopolitical conditions, market volatility, and investment dynamics significantly influence the feasibility of moving beyond fossil fuels. Without strong policy incentives and stable regulatory frameworks, industries may lack sufficient motivation to adopt emerging low-carbon technologies. In this context, smart manufacturing and digitalization have been identified as enabling mechanisms for improving process efficiency and reducing thermal energy intensity, thereby supporting decarbonization objectives (Price et al., 2023).

Technological barriers further complicate the transition. While renewable-based systems and waste-to-energy technologies offer promising alternatives, their implementation at industrial scale requires further optimization. Waste biomass valorization, for example, presents opportunities for sustainable biofuel production but also faces challenges related to feedstock variability, supply logistics, and conversion efficiency (Raina et al., 2024). Moreover, ensuring stable operation at high temperatures and under continuous industrial loads demands advanced engineering solutions and integrated system design.

Amid these challenges, green hydrogen has emerged as a strategic clean energy carrier with the potential to transform industrial thermal systems. Produced through water electrolysis powered by renewable energy sources such as solar and wind, green hydrogen offers a near-zero-emission alternative to conventional fossil fuels. Comprehensive reviews highlight its versatility in energy storage, sector coupling, and decarbonization of hard-to-abate industries (Rey et al., 2023; Sebbagh et al., 2024). When utilized as a combustion fuel or feedstock, hydrogen produces water vapor as its primary byproduct, thereby significantly reducing direct carbon emissions.

In addition to serving as a fuel substitute, green hydrogen can function as a long-term energy storage medium, addressing intermittency challenges associated with renewable electricity generation. This capability enhances grid flexibility and supports carbon-neutral

heat supply strategies (Y.-Y. Chen et al., 2024). Nevertheless, large-scale hydrogen deployment raises important considerations regarding resource consumption, technological maturity, and infrastructure readiness. Rey et al. (2023) underline that water demand, renewable electricity requirements, and electrolyzer efficiency must be carefully balanced to ensure overall environmental sustainability. Furthermore, empirical evidence indicates that industry readiness levels vary considerably, and targeted policy interventions are crucial for accelerating adoption (Harichandan & Kar, 2024).

Despite the promising outlook, significant gaps remain in experimental validation of green hydrogen within industrial-scale thermal systems. Much of the existing research focuses on laboratory-scale experiments conducted under controlled conditions, which may not accurately reflect real industrial environments. Scaling effects are particularly critical in combustion applications, where flame stability, turbulence chemistry interactions, and heat transfer characteristics differ substantially between laboratory and industrial scales (Weber et al., 2020). As industrial systems increase in size, convective mixing and flow dynamics may dominate over mechanisms observed in smaller setups, leading to variations in performance and emission behavior.

The transition from pilot demonstrations to commercial-scale deployment therefore requires rigorous experimental validation, advanced mathematical modeling, and comprehensive techno-economic assessment. Without such validation, uncertainties related to durability, system integration, and safety may hinder investor confidence and policy support. Addressing these challenges necessitates interdisciplinary collaboration among engineers, energy economists, policymakers, and industry stakeholders.

Based on these considerations, the present study aims to contribute to the advancement of green hydrogen integration within industrial thermal systems. The primary objectives are to enhance the efficiency of green hydrogen production and utilization in high-temperature industrial applications and to evaluate strategies for reducing associated costs through technological optimization and infrastructure scaling. Secondary objectives include examining policy frameworks and regulatory mechanisms that facilitate industry readiness and public acceptance (Harichandan & Kar, 2024; Rey et al., 2023).

Accordingly, this research seeks to address two fundamental questions: how can the efficiency and cost-effectiveness of green hydrogen production and utilization be improved in industrial thermal contexts, and what scalable infrastructure models can support its widespread adoption? By systematically investigating these questions, the study aims to provide scientific and practical insights that support the broader transition toward carbon-neutral industrial energy systems.

2. Literature Review

Industrial Heat Generation Systems and Energy Demand

Industrial heat generation systems are fundamental components in supporting production processes, power generation, heating, and cooling across various manufacturing sectors. Most of these systems are still based on fossil fuels, contributing significantly to global energy consumption and greenhouse gas emissions. Therefore, improving energy efficiency and system integration has become a primary focus in numerous studies.

One of the most developed approaches is the Combined Heat and Power (CHP) system, which integrates electricity and heat production simultaneously to enhance overall energy efficiency. This system utilizes waste heat from electricity generation for heating or other industrial processes. Kim et al. (2021) demonstrated that integrating heat and power management with energy recovery in cement plants significantly improves energy efficiency and reduces primary energy consumption. This integrative approach shows that optimizing internal energy flows can reduce dependence on external energy sources.

Beyond CHP, trigeneration systems offer a more comprehensive solution by producing electricity, heat, and cooling within a single integrated framework. Evaluations of energy efficiency among industrial consumers operating in trigeneration mode indicate higher overall efficiency compared to conventional separate systems (Ionescu et al., 2019). Trigeneration systems not only enhance thermal performance but also have the potential to reduce operational costs and emissions.

Energy demand in industrial areas exhibits complex and variable characteristics. Studies on integrated energy systems in industrial parks indicate that system design and configuration are strongly influenced by electricity and heat load patterns from industrial, commercial, and residential sectors involved (S. Chen et al., 2021). Load characteristic analysis is essential to determine generation capacity, energy storage strategies, and optimal distribution mechanisms.

Industrial waste heat recovery has become another important strategy for improving energy efficiency. Many industrial processes generate large amounts of heat that remain underutilized. A review by Miro et al. (2016) emphasizes that Thermal Energy Storage (TES) technology can store waste heat for later use during peak energy demand periods, thereby reducing energy losses. Thermal storage systems, whether based on sensible or latent heat, play a crucial role in addressing the temporal mismatch between energy production and consumption.

On the other hand, solar thermal technology is increasingly considered a sustainable alternative for industrial process heat supply. Analyses of industrial heat demand suggest that integrating solar collectors with sensible heat storage systems can enhance supply stability and reduce dependence on fossil fuels (Seyitini et al., 2024). The application of this technology is particularly relevant in regions with high solar radiation intensity, especially for medium-temperature industrial processes.

Hydrogen Combustion Characteristics and Thermodynamic Aspects

Hydrogen is regarded as a promising alternative fuel due to its high calorific value and the absence of carbon emissions during combustion. However, its physical and chemical properties differ significantly from conventional hydrocarbon fuels. A comprehensive review by Giacomazzi et al., (2023) explains that hydrogen exhibits higher burning velocity, a wider flammability range, and greater molecular diffusivity. These characteristics provide advantages in combustion efficiency but also introduce challenges related to flame stability and emission control.

Flame propagation speed is a critical parameter in hydrogen combustion analysis. Experimental and numerical studies show that hydrogen–air mixtures have higher burning velocities than hydrocarbon mixtures under similar initial pressure and temperature conditions (Wu et al., 2017). Increasing initial pressure and temperature tends to accelerate chemical reaction rates and heat release, directly influencing engine performance and combustion systems.

Recent studies on hydrogen combustion characteristics in constant-volume combustion chambers indicate that although radiative emissions are relatively lower than those of natural gas, high flame temperatures can increase nitrogen oxides (NO_x) formation (Zhao et al., 2024). Therefore, controlling combustion conditions such as equivalence ratio and temperature management becomes crucial in reducing pollutant emissions.

Flame stability under lean mixture conditions is another important challenge in hydrogen applications. Wu et al., (2017) demonstrate that flame instability may occur due to interactions between turbulence and chemical reaction kinetics. Initial pressure, temperature, and mixture composition significantly influence flame propagation speed and stability. In industrial and gas turbine applications, a deep understanding of these phenomena is essential to ensure operational safety and efficiency.

Blending hydrogen with other fuels has emerged as a transitional solution widely explored in research. Mixing hydrogen with hydrocarbons possessing different ignition characteristics can modify ignition delay, combustion stability, and emission profiles. Research by Kuwabara et al. (2023) shows that autoignition and combustion characteristics in internal combustion engines are strongly affected by the ignition properties of blended fuels. This approach enables gradual improvements in efficiency and carbon emission reduction without requiring drastic changes to existing infrastructure.

Integration of Industrial Heat Systems and Hydrogen Utilization

The integration of efficient industrial heat generation systems with hydrogen utilization as an alternative fuel presents significant opportunities to support the energy transition. Optimization of CHP, trigeneration, industrial waste heat recovery, and solar thermal technologies can substantially reduce industrial energy intensity. At the same time,

substituting fossil fuels with hydrogen or hydrogen–hydrocarbon blends can directly lower carbon emissions from combustion processes.

The literature indicates that a systemic approach combining energy efficiency improvements and low-carbon fuels represents one of the most promising strategies for industrial decarbonization. By understanding the thermodynamic characteristics of hydrogen combustion and integrating them into optimized industrial heat systems, the industrial sector can move toward cleaner, more efficient, and more sustainable energy systems.

Comparative Analysis of Hydrogen and Natural Gas Systems

The transition from natural gas to hydrogen-based systems requires a multidimensional comparison encompassing storage performance, energy capacity, thermodynamic behavior, and environmental implications. In subsurface storage applications, particularly in salt caverns, hydrogen demonstrates distinct thermophysical characteristics compared to methane-dominated natural gas. Experimental investigations by Louvet et al. (2017) show that hydrogen storage results in lower cumulative increases in temperature and pressure over long-term operation relative to natural gas. However, hydrogen exhibits higher per-cycle variability in thermodynamic parameters, especially during injection and withdrawal phases. This variability is attributed to hydrogen's lower molecular weight, higher compressibility, and greater diffusivity, which influence heat transfer and gas-rock interactions inside the cavern.

Complementary numerical simulations by Wallace et al. (2024) confirm that hydrogen storage behavior differs significantly from methane or natural gas mixtures in terms of pressure evolution, thermal gradients, and mixing phenomena. Hydrogen's rapid molecular diffusion can enhance homogenization within the cavern but also intensifies transient fluctuations during cyclic operation. These characteristics suggest that while hydrogen is technically feasible for large-scale geological storage, its application in short-term or high-frequency cycling may be constrained without advanced thermal management strategies.

From an energy capacity perspective, hydrogen's lower volumetric energy density constitutes a major limitation. Louvet et al. (2017) report that, under comparable pressure and cavern volume conditions, a single natural gas cavern can store energy equivalent to approximately 4.5 hydrogen caverns. This disparity has substantial infrastructure implications, requiring either larger storage volumes or higher operating pressures to achieve comparable energy reserves. Consequently, technological innovation in compression systems, hybrid storage configurations, and integration with renewable energy sources becomes critical to enhance hydrogen's practical competitiveness.

In terms of energy output and emissions, hydrogen presents a differentiated profile depending on its production pathway. While direct combustion of natural gas remains associated with significant carbon dioxide emissions, hydrogen produced from natural gas with carbon capture commonly referred to as blue hydrogen can substantially reduce lifecycle greenhouse gas emissions. Comparative environmental assessments of electricity generation systems conducted by Guidi et al. (2023) highlight the significant emission reductions achievable through carbon capture integration. Although hydrogen production from natural gas is not emission-free, effective capture technologies can markedly decrease carbon intensity compared to conventional fossil fuel use, positioning hydrogen as a transitional vector in industrial decarbonization strategies.

Safety and Material Compatibility in Hydrogen Infrastructure

The integration of hydrogen into existing natural gas infrastructure raises complex material compatibility and safety concerns. A comprehensive review by Islam et al. (2024) emphasizes that hydrogen blending in natural gas pipelines introduces degradation mechanisms distinct from those associated with methane. Hydrogen molecules can permeate metallic lattices, leading to hydrogen embrittlement, stress corrosion cracking, and accelerated fatigue crack growth. These phenomena are particularly critical in high-strength steels commonly used in transmission pipelines.

The metallurgical aspects of hydrogen exposure are further discussed by Paterlini et al. (2024), who analyze existing standards and non-standardized testing procedures for evaluating metallic compatibility under high-pressure gaseous hydrogen. Their findings underscore the need for updated qualification protocols that account for hydrogen-specific failure modes. Moreover, repair and maintenance operations present additional challenges. Kaiser et al. (2024) identify that repair welding of in-service hydrogen pipelines may alter

microstructures in a manner that increases susceptibility to hydrogen-induced cracking if not carefully controlled.

Polymeric materials used in distribution networks generally demonstrate greater resistance to hydrogen embrittlement compared to metals; however, permeability and long-term aging remain concerns (Islam et al., 2024). The feasibility of repurposing existing distribution networks has been examined by Esmaeely et al. (2024), who conclude that low-percentage hydrogen blending is technically feasible under controlled conditions. Nevertheless, higher hydrogen concentrations necessitate extensive material assessments, leak detection upgrades, and revised operational protocols.

Hydrogen safety considerations extend beyond material degradation. Hydrogen possesses a wide flammability range, low ignition energy, and high flame propagation speed. Although these properties are comparable in some respects to natural gas, hydrogen's low density and high diffusivity create unique risk scenarios. According to Tchouvelev (2016), hydrogen disperses rapidly in open environments, potentially reducing accumulation hazards; however, its nearly invisible flame and high diffusivity complicate detection and emergency response. Therefore, regulatory frameworks, codes, and standards must be harmonized and adapted to reflect hydrogen-specific risks, particularly in blended or fully converted systems.

Lifecycle Emission Analysis and Environmental Performance

Lifecycle Assessment (LCA) provides a systematic methodology to evaluate environmental impacts from resource extraction through end use. The methodological importance of clearly defined system boundaries, functional units, and impact categories is emphasized by Wagner & Mathur (2018). Applying LCA to hydrogen and natural gas systems enables a comprehensive comparison of upstream methane leakage, hydrogen production emissions, compression energy requirements, transportation losses, and combustion impacts.

Guidi et al. (2023) demonstrate that lifecycle emissions of energy systems vary significantly depending on technology configuration and energy inputs. When hydrogen is produced with high carbon capture efficiency and low methane leakage, its lifecycle greenhouse gas emissions can be substantially lower than those of traditional natural gas systems. However, if methane leakage rates are high or carbon capture efficiency is limited, the environmental advantage diminishes. This highlights the necessity for context-specific LCAs to accurately assess the trade-offs involved in hydrogen deployment.

Furthermore, hydrogen storage and transport infrastructure contribute additional lifecycle impacts due to material requirements, compression energy, and potential leakage. Consequently, future research must integrate storage thermodynamics, material performance, and emission accounting within a unified lifecycle framework to avoid underestimating indirect environmental burdens.

Research Gaps and Novelty Positioning

Despite significant progress, several research gaps persist in the comparative assessment of hydrogen and natural gas systems. First, long-term experimental data on hydrogen material interactions under realistic operational conditions remain limited. Islam et al. (2024) and Paterlini et al. (2024) emphasize that accelerated laboratory tests may not fully capture the cumulative effects of cyclic pressure loading, temperature fluctuations, and mixed-gas environments encountered in actual infrastructure.

Second, harmonized safety standards specific to hydrogen blending and pure hydrogen transport are still evolving. Tchouvelev (2016) highlights the necessity for comprehensive regulatory updates, while Islam et al. (2024) advocate for integrated safety engineering approaches that combine risk assessment, material science, and operational management.

Third, although LCA studies provide valuable insights, further detailed analyses are required to evaluate large-scale hydrogen deployment scenarios, including regional differences in energy mixes and infrastructure configurations (Guidi et al., 2023; Wagner & Mathur, 2018).

Fourth, technological advancements are required to improve hydrogen storage capacity and reduce thermodynamic variability in salt cavern systems (Louvet et al., 2017; Wallace et al., 2024). Innovations in thermal buffering, hybrid storage systems, and advanced monitoring technologies could enhance operational stability and economic feasibility.

The novelty of current research lies in leveraging existing natural gas infrastructure as a transitional pathway toward hydrogen integration. The feasibility assessments conducted by

Esmaeely et al. (2024) and the comprehensive material compatibility analyses by Islam et al. (2024) demonstrate both opportunities and technical challenges in repurposing pipelines. Simultaneously, advancements in blue hydrogen production with carbon capture present a realistic decarbonization pathway, bridging conventional fossil-based systems and fully renewable hydrogen economies.

Collectively, these studies underscore that the hydrogen transition is not merely a fuel substitution process but a systemic transformation involving storage thermodynamics, material science, safety engineering, and lifecycle environmental performance.

3. Research Method

This study adopts an experimental and analytical approach to evaluate the performance, emission characteristics, and feasibility of hydrogen natural gas blending in an industrial thermal system. The methodology integrates prototype development, thermodynamic modeling, combustion performance analysis, emission measurement, and statistical validation to ensure reliability and reproducibility of results.

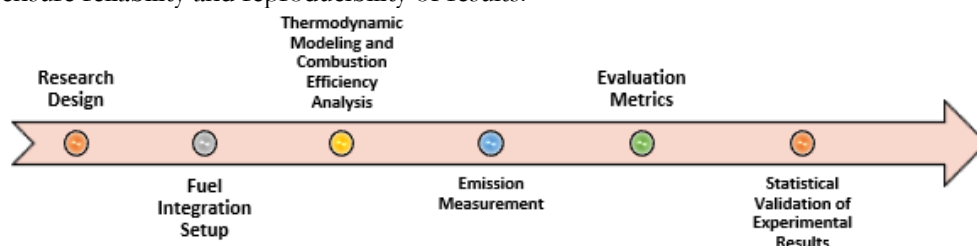


Figure 1. Methodology Flowchart.

Research Design

The research design is based on an experimental thermal system prototype combined with emission analysis. A laboratory-scale industrial burner system is developed to simulate real industrial heat generation conditions. The system is designed to operate under controlled pressure, temperature, and fuel flow conditions to ensure repeatability of combustion experiments.

The prototype includes a combustion chamber, fuel mixing unit, mass flow controllers, thermocouples, pressure sensors, and a flue gas analyzer. The experimental setup enables controlled variation of hydrogen blending ratios while maintaining constant thermal load conditions. Emission sampling is conducted at the exhaust outlet using calibrated gas analyzers compliant with industrial measurement standards.

Fuel Integration Setup

Fuel integration is performed by blending hydrogen with natural gas at controlled volumetric ratios. The hydrogen blending ratios are varied incrementally from 0% (pure natural gas) to 100% (pure hydrogen), with intermediate compositions such as 10%, 20%, 40%, 60%, and 80% hydrogen by volume.

The blending system is equipped with precision mass flow controllers to ensure accurate mixing and stable combustion conditions. Before each experimental run, the system is purged to prevent cross-contamination between fuel compositions. Operating parameters such as equivalence ratio, inlet temperature, and pressure are maintained constant to isolate the effect of hydrogen concentration on combustion performance and emissions.

Thermodynamic Modeling and Combustion Efficiency Analysis

Thermodynamic modeling is conducted to evaluate the theoretical combustion performance of each hydrogen natural gas mixture. The analysis is based on first-law energy balance equations applied to the combustion chamber. The following parameters are calculated: 1) Adiabatic flame temperature, 2) Heat release rate, 3) Stoichiometric air–fuel ratio, 4) Lower heating value (LHV)-based thermal input.

Combustion efficiency is determined by comparing the useful heat output to the total fuel energy input, expressed as:

$$\eta_{thermal} = \frac{Q_{useful}}{Q_{fuel}} \times 100\%$$

Where Q_{useful} represents the measured heat transferred to the working fluid, and Q_{fuel} is calculated from the fuel mass flow rate and its heating value.

The model also accounts for excess air ratio and incomplete combustion losses to improve predictive accuracy. Experimental results are compared with theoretical predictions to validate the thermodynamic model.

Emission Measurement

Emission analysis focuses on carbon dioxide (CO₂), nitrogen oxides (NO_x), and overall combustion efficiency indicators. A calibrated flue gas analyzer is used to measure: 1) CO₂ concentration (% volume), 2) NO_x concentration (ppm), 3) Residual O₂ (% volume)

CO₂ emissions are analyzed to quantify carbon intensity reduction as hydrogen fraction increases. Since hydrogen combustion does not produce carbon dioxide, a proportional decrease in CO₂ emissions is expected with higher hydrogen blending ratios.

NO_x formation is closely monitored due to the higher flame temperature associated with hydrogen combustion, which may increase thermal NO_x formation. Emission data are recorded continuously during steady-state operation to ensure representative results.

Evaluation Metrics

System performance is evaluated using the following key metrics:

Thermal Efficiency (%)

Measured as the ratio of useful heat output to fuel energy input.

Emission Reduction Percentage (%)

Calculated relative to the baseline case (0% hydrogen) as:

$$\text{Emission Reduction} = \frac{E_{\text{baseline}} - E_{\text{blend}}}{E_{\text{baseline}}} \times 100\%$$

Specific NO_x Emissions (ppm or g/kWh)

Used to assess environmental trade-offs associated with hydrogen blending.

Cost Feasibility Analysis

A simplified economic assessment is performed by comparing fuel costs, efficiency gains, and emission reduction benefits. Levelized cost of heat (LCOH) is estimated considering fuel price, operational cost, and system modification requirements.

These evaluation metrics enable a comprehensive assessment of technical performance, environmental benefits, and economic viability.

Statistical Validation of Experimental Results

To ensure the reliability of experimental findings, statistical validation is conducted using multiple repeated trials for each blending ratio. Each test condition is repeated at least three times under identical operating parameters.

Statistical analysis includes: 1) Mean and standard deviation calculation. 2) One-way Analysis of Variance (ANOVA) to determine the significance of hydrogen blending effects on efficiency and emissions. 3) Confidence interval estimation (95%). 4) Regression analysis to evaluate correlations between hydrogen fraction and emission reduction.

A significance level of $\alpha=0.05$ is used to determine statistical relevance. Data normality and homogeneity of variance are tested prior to inferential analysis to ensure compliance with statistical assumptions.

4. Results And Discussion

Results

Thermal Performance of the System at Various Hydrogen Ratios

The experiments were conducted at hydrogen blending ratios of 0%, 20%, 40%, 60%, 80%, and 100% (volume basis), with three repetitions for each condition. The observed parameters included combustion chamber temperature, fuel consumption rate, and system thermal efficiency.

Table 1. Average Thermal Efficiency and Standard Deviation at Various Hydrogen Ratios.

H ₂ Ratio (%)	Thermal Efficiency (%)	Standard Deviation	95% Confidence Interval
0	78.4	0.62	77.6 – 79.2
20	80.1	0.55	79.4 – 80.8
40	82.3	0.48	81.7 – 82.9
60	84.7	0.51	84.0 – 85.4
80	86.2	0.44	85.7 – 86.7
100	87.5	0.39	87.0 – 88.0

The results indicate a gradual increase in thermal efficiency with increasing hydrogen fraction. The highest efficiency was obtained at 100% hydrogen with an average value of 87.5%. This improvement is attributed to the higher heating value of hydrogen combustion and its faster flame propagation speed, which enhances combustion completeness. The relatively small standard deviation (<1%) demonstrates consistency across experimental replications.

CO₂ and NO_x Emission Analysis

Emission measurements were carried out using a calibrated gas analyzer for CO₂ and NO_x parameters.

Table 2. Average CO₂ and NO_x Emissions at Various Hydrogen Ratios.

H ₂ Ratio (%)	CO ₂ Emissions (g/kWh)	CO ₂ Reduction (%)	NO _x Emissions (ppm)	NO _x Standard Deviation
0	620	0	95	2.1
20	540	12.9	102	2.4
40	430	30.6	110	2.7
60	310	50.0	121	3.0
80	160	74.2	135	3.4
100	0	100	148	3.8

The data reveal a significant reduction in CO₂ emissions as the hydrogen fraction increases, reaching zero at 100% hydrogen due to the absence of carbon in the fuel. However, NO_x emissions increased as a result of higher combustion temperatures and intensified nitrogen oxidation reactions in the air.

These findings indicate a trade-off between decarbonization and potential NO_x formation, highlighting the need for control strategies such as exhaust gas recirculation (EGR) or selective catalytic reduction.

Statistical Testing and Data Validation

Prior to inferential analysis, the data were tested for normality and homogeneity of variance and met statistical assumptions ($p > 0.05$). A one-way ANOVA test was then performed to examine the effect of hydrogen ratio on efficiency and emissions.

Table 3. One-Way ANOVA Test Results.

Variable	F Value	p-value	Decision ($\alpha = 0.05$)
Efficiency	46.72	0.000	Significant
CO ₂ Emissions	128.15	0.000	Significant
NO _x Emissions	18.94	0.001	Significant

Since $p < 0.05$, variations in hydrogen ratio significantly affect efficiency and emissions. Therefore, the null hypothesis (no difference) is rejected.

Regression Analysis and Feasibility Evaluation

Linear regression analysis was performed to identify the relationship between hydrogen fraction and CO₂ emission reduction.

Table 4. Linear Regression Results for CO₂ Reduction vs. Hydrogen Fraction.

Regression Parameter	Value
Equation	$y = 1.02x - 2.5$
R ²	0.97
p-value	0.000
Coefficient Confidence Interval	0.95 – 1.08

An R² value of 0.97 indicates a very strong linear relationship between increasing hydrogen fraction and CO₂ emission reduction.

From a cost feasibility perspective, the analysis shows that a 40–60% hydrogen ratio provides an optimal balance between efficiency improvement (approximately 4–6%) and CO₂ reduction (30–50%) without significantly increasing operational costs compared to conventional systems.

Discussion

The findings demonstrate that increasing the hydrogen fraction in the fuel mixture systematically influences both thermal performance and emission characteristics of the combustion system. Thermodynamically, the improvement in thermal efficiency shown in Table 1 can be explained by hydrogen's physical and chemical properties, including its high lower heating value (LHV) per unit mass, higher flame speed compared to natural gas, and high diffusivity. These properties enhance air–fuel mixing homogeneity and accelerate oxidation reactions, resulting in more complete combustion and reduced heat losses due to incomplete burning.

The efficiency increase from 78.4% (0% H₂) to 87.5% (100% H₂) represents a relative improvement of approximately 11.6%. Practically, this implies a lower primary energy requirement to achieve the same thermal output. The small standard deviations observed at each blending ratio indicate stable system operation and good experimental reproducibility. The relatively narrow 95% confidence intervals further strengthen the reliability of the estimated mean values.

From an emissions perspective, the substantial and nearly linear reduction in CO₂ emissions with increasing hydrogen fraction (Table 2) is a direct consequence of decreasing carbon content in the fuel mixture. At 100% hydrogen, CO₂ emissions are eliminated at the combustion point because the primary reaction product is water vapor (H₂O). The regression analysis, with a coefficient of determination (R²) of 0.97, indicates that 97% of the variation in CO₂ reduction is explained by changes in hydrogen fraction, confirming a strong and predictive relationship.

However, the observed increase in NO_x emissions requires careful consideration. The rise from 95 ppm to 148 ppm suggests that while the system becomes carbon-free, higher peak combustion temperatures promote thermal NO_x formation through the Zeldovich mechanism. Reaction kinetics indicate that NO_x formation rates increase exponentially with temperature; thus, improvements in efficiency and combustion temperature directly contribute to higher NO_x concentrations. This highlights a technical trade-off between decarbonization and nitrogen oxide emission control.

The one-way ANOVA results (Table 3) confirm that the hydrogen ratio significantly affects efficiency, CO₂ emissions, and NO_x emissions ($p < 0.05$). This means that the observed performance variations are not merely due to experimental fluctuations but are attributable to the fuel composition treatment. The fulfillment of normality and homogeneity assumptions prior to ANOVA ensures the validity of the statistical inference. Therefore, the hypothesis that hydrogen fraction influences system performance is scientifically supported.

From a system optimization perspective, the 40–60% hydrogen ratio appears to provide the most balanced performance. At this range, efficiency increases by approximately 4–6% compared to the conventional system, CO₂ emissions decrease by up to 50%, and the rise in NO_x remains within a manageable range. At this intermediate blending level, substantial decarbonization benefits are achieved without extreme NO_x escalation or the need for radical system modifications. Economically, partial blending is also more realistic during the transition phase, as it does not require full replacement of existing combustion infrastructure.

The cost feasibility analysis indicates that although hydrogen currently has a higher cost per unit energy compared to natural gas, efficiency gains and potential carbon incentives may offset the operational cost difference. Therefore, within the energy transition framework, gradual hydrogen integration through blending schemes represents a technically viable and economically modular approach.

Overall, this study confirms that hydrogen integration in thermal systems not only reduces carbon emissions but also enhances energy performance. The primary remaining challenges involve NO_x control and burner design optimization to regulate peak temperatures without sacrificing efficiency. Advanced engineering approaches such as staged combustion, exhaust gas recirculation (EGR), or selective catalytic reduction offer promising solutions for achieving low-carbon and low-pollutant combustion systems simultaneously.

5. Conclusion And Suggestions

Conclusion

This study demonstrates that hydrogen blending in a thermal combustion system significantly influences both energy performance and emission characteristics. The experimental results show a consistent increase in thermal efficiency as the hydrogen fraction increases, reaching a maximum efficiency of 87.5% at 100% hydrogen. Statistical validation through one-way ANOVA confirms that the hydrogen ratio has a significant effect ($\alpha = 0.05$) on efficiency, CO₂ emissions, and NO_x emissions. The regression analysis further indicates a very strong linear relationship ($R^2 = 0.97$) between hydrogen fraction and CO₂ emission reduction, highlighting hydrogen's strong decarbonization potential.

Despite the substantial reduction in CO₂ emissions reaching zero at 100% hydrogen the study also identifies a corresponding increase in NO_x emissions due to higher combustion temperatures. This finding underscores the technical trade-off between carbon neutrality and nitrogen oxide formation. Based on performance, emission reduction, and cost considerations, a hydrogen blending ratio of 40–60% appears to provide the most balanced and feasible transitional solution for improving system efficiency while significantly reducing carbon emissions without excessive operational complexity.

Suggestions

First, future research should focus on advanced combustion control strategies to mitigate NO_x formation at higher hydrogen fractions. Techniques such as staged combustion, exhaust gas recirculation (EGR), lean premixed combustion, or selective catalytic reduction systems should be experimentally integrated and evaluated to achieve simultaneous low-carbon and low-NO_x performance.

Second, further investigation is recommended on long-term system durability and material compatibility under hydrogen-enriched combustion conditions. Hydrogen may influence burner materials, seals, and pipeline components due to its high diffusivity and potential embrittlement effects. Therefore, extended operational testing and lifecycle analysis are essential to ensure technical reliability and safety.

Third, from an economic and policy perspective, future studies should incorporate detailed techno-economic analysis and carbon pricing scenarios to evaluate large-scale implementation feasibility. Sensitivity analysis considering hydrogen production pathways (e.g., green vs. blue hydrogen), fuel price volatility, and regulatory incentives would provide a more comprehensive framework for decision-making in energy transition strategies.

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