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Research Article

THERMO-ECONOMIC AND EMISSION ASSESSMENT OF AMMONIA-HYDROGEN DUAL-FUEL COMBUSTION IN ADVANCED INTERNAL COMBUSTION ENGINES FOR DECARBONIZED POWER GENERATION

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Abstract

Ammonia–hydrogen dual-fuel combustion offers a promising pathway for dispatchable low-carbon power generation, yet its practical viability depends on balancing efficiency, cost, and nitrogen-based emissions. This study aimed to evaluate the thermodynamic, economic, and environmental performance of ammonia–hydrogen combustion in an advanced internal combustion engine. A quantitative experimental design combined single-cylinder engine testing, thermo-economic modeling, life-cycle emission assessment, statistical analysis, and multi-objective optimization. Hydrogen energy fractions from 0% to 40% were examined across multiple loads and ignition settings, with selected tests incorporating exhaust-gas recirculation. Results showed that hydrogen enrichment shortened ignition delay, improved combustion stability, increased brake thermal efficiency, and reduced ammonia slip and nitrous oxide emissions. Hydrogen fractions between 20% and 30% provided the most balanced performance, while 40% enrichment produced only marginal efficiency gains and higher nitrogen-oxide emissions and electricity costs. A 30% hydrogen fraction with 10% exhaust-gas recirculation maintained 37.60% brake thermal efficiency and reduced nitrogen oxides by more than 40%. Renewable fuel pathways achieved the lowest life-cycle emissions but the highest levelized electricity cost. The study concludes that coordinated optimization of fuel composition, combustion control, emission mitigation, and fuel-production pathways is essential for credible decarbonized power generation under technically stable and economically plausible operating conditions at scale.

Keywords: Ammonia combustion; Decarbonized power; Dual-fuel engine; Emission assessment; Thermo-economic analysis.

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INTRODUCTION

Global efforts to decarbonize electricity generation have intensified the search for energy carriers capable of reducing dependence on fossil fuels while maintaining reliable and dispatchable power production (Ali & Wang, 2026). Renewable electricity from solar and wind resources has expanded rapidly, yet its intermittent nature creates continuing demand for flexible generation technologies that can respond to fluctuations in supply and consumption (Kim et al., 2025). Advanced internal combustion engines remain relevant in this transition because they provide rapid start-up, operational flexibility, high power density, and compatibility with distributed power systems (D. Wu et al., 2024). This paragraph should introduce the need for low-carbon fuels that can enable internal combustion engines to support decarbonized electricity generation without sacrificing reliability or operational responsiveness.

Ammonia has attracted increasing attention as a carbon-free energy carrier because its molecular structure contains no carbon and its combustion does not directly produce carbon dioxide (Lv et al., 2025). Established infrastructure for ammonia production, storage, transportation, and international trade also gives it practical advantages over several emerging fuels (Fu et al., 2025). Ammonia can potentially store renewable energy over long periods and transport hydrogen-derived energy across large geographic distances (Fisher et al., 2024). Its relatively high liquefaction temperature simplifies storage compared with pure hydrogen. This paragraph should present ammonia as a promising fuel for stationary power generation while recognizing that its physical and chemical properties create substantial combustion challenges.

Hydrogen can complement ammonia combustion because it possesses a high flame speed, wide flammability range, low ignition energy, and strong capacity to stabilize slow-burning fuel mixtures (Xu et al., 2025). Ammonia–hydrogen dual-fuel operation may therefore overcome several limitations associated with pure ammonia, including delayed ignition, low combustion velocity, narrow stable operating ranges, and incomplete fuel oxidation (Zhou et al., 2025). Hydrogen enrichment can improve combustion stability and thermal efficiency, yet excessive hydrogen addition may alter nitrogen-oxide formation, increase fuel costs, and complicate storage requirements (X. Wang et al., 2025). This paragraph should establish dual-fuel combustion as a technically promising but multidimensional optimization problem involving performance, economics, emissions, and operational safety.

Pure ammonia combustion in internal combustion engines is constrained by poor ignition characteristics, low laminar flame speed, and relatively high resistance to stable flame propagation (Abokhalil et al., 2026). These properties can cause incomplete combustion, cycle-to-cycle variation, reduced indicated efficiency, and elevated emissions of unburned ammonia. Ammonia slip presents environmental and health concerns because ammonia is toxic, corrosive, and capable of contributing indirectly to particulate formation (Wei et al., 2026). This paragraph should identify the first research problem as the difficulty of achieving stable, efficient, and clean engine operation when ammonia is used as the dominant fuel.

Nitrogen-based emissions constitute another major technical challenge (Soumith et al., 2025). Ammonia combustion can generate nitrogen oxides through thermal, fuel-bound, and intermediate chemical pathways, while incomplete reactions may produce nitrous oxide, an emission with substantial climate impact (Q. Wu et al., 2026). Hydrogen enrichment can improve combustion completeness but may raise peak temperatures and accelerate selected nitrogen-oxide formation mechanisms. Engine operating conditions such as equivalence ratio, compression ratio, ignition timing, load, hydrogen fraction, and exhaust-gas recirculation strongly influence these outcomes (Zhu et al., 2026). This paragraph should explain that reducing carbon dioxide alone is insufficient when the combustion process creates other environmentally damaging emissions.

Economic feasibility remains uncertain because low-carbon ammonia and hydrogen are generally more expensive than conventional fossil fuels, particularly when they are produced using renewable electricity (Raheja et al., 2026). Fuel price, engine efficiency, maintenance demand, storage infrastructure, emission-control systems, and equipment lifetime collectively determine the cost of generated electricity. A technically efficient operating condition may remain economically unattractive, while a low-cost configuration may produce unacceptable emissions or unstable combustion (Priyak & Arun, 2026). This paragraph should formulate the central research problem as the absence of a balanced assessment that integrates thermodynamic performance, fuel economics, emission behavior, and practical operating constraints.

The primary objective of the study is to evaluate the thermodynamic performance of ammonia–hydrogen dual-fuel combustion in an advanced internal combustion engine intended for low-carbon power generation (Priyak & Arun, 2026). Performance indicators should include brake thermal efficiency, indicated thermal efficiency, brake-specific fuel consumption, combustion duration, ignition delay, peak cylinder pressure, heat-release characteristics, and exhaust-gas temperature (Nutakki et al., 2024). This paragraph should clarify that the research seeks to determine how different hydrogen-energy fractions and engine operating conditions influence fuel conversion, combustion stability, and useful power output.

The second objective is to quantify the economic consequences of replacing conventional fuel with ammonia–hydrogen mixtures (Sui et al., 2025). The analysis should consider fuel-production cost, storage and delivery expenses, engine-conversion requirements, operational and maintenance costs, emission-control expenditure, and levelized cost of electricity (Y. Wu, 2025). Sensitivity analysis should examine the influence of ammonia price, hydrogen price, carbon pricing, annual operating hours, system efficiency, and equipment lifetime (Morrone et al., 2026). This paragraph should state that the study aims to identify operating conditions and market assumptions under which dual-fuel generation may become economically competitive.

The third objective is to assess the emission profile of ammonia–hydrogen combustion and identify trade-offs among carbon reduction, nitrogen-based emissions, combustion efficiency, and economic performance (Feng et al., 2024). Relevant indicators should include carbon dioxide, nitrogen oxides, nitrous oxide, unburned ammonia, hydrogen slip, and any remaining carbon-related emissions associated with auxiliary fuels or upstream fuel production (Manesh & Liu, 2025). This paragraph should establish the intention to develop an integrated optimization framework capable of identifying operating regions that provide acceptable performance, manageable cost, and minimal environmental impact.

Existing studies have extensively examined the fundamental combustion characteristics of ammonia, hydrogen, and their mixtures (W. Li et al., 2024). Experimental and numerical investigations have provided valuable knowledge concerning flame speed, ignition behavior, chemical kinetics, combustion instability, and nitrogen-oxide formation (Mauro et al., 2025). Many studies nevertheless focus on laboratory-scale flames, constant-volume chambers, burners, or isolated engine-performance indicators (Jia et al., 2024). This paragraph should identify a scale-related gap between fundamental combustion research and integrated assessments of complete engine-based power-generation systems operating under realistic load and control conditions.

Engine research on ammonia–hydrogen mixtures commonly emphasizes thermal efficiency, combustion stability, or selected exhaust emissions (Y. Li et al., 2025). Economic analysis is frequently addressed separately or omitted entirely, leaving uncertainty about whether technically improved operating conditions can support commercially viable electricity production (Lin et al., 2026). Studies that calculate fuel costs may also rely on fixed price assumptions without examining uncertainty in renewable ammonia, electrolytic hydrogen, carbon pricing, and infrastructure costs (Zhang et al., 2026). This paragraph should highlight the need for a thermo-economic framework that directly connects combustion performance with electricity-generation costs and changing market conditions.

Environmental assessments often report reductions in direct carbon dioxide emissions without fully accounting for nitrogen-based emissions or upstream fuel-production pathways

(Shabruhi Mishamandani et al., 2026). Ammonia produced from fossil-based hydrogen may retain a substantial life-cycle carbon footprint, while renewable ammonia can provide deeper decarbonization at a higher cost (P. Wang et al., 2024). Nitrous oxide and ammonia slip may also undermine environmental benefits when they are not adequately controlled (Turja et al., 2024). This paragraph should emphasize the gap created by narrow tailpipe-emission analysis and establish the need for a broader framework that distinguishes direct combustion emissions from upstream and life-cycle environmental impacts.

The novelty of the proposed study lies in integrating thermodynamic, economic, and emission assessments within a unified evaluation of ammonia–hydrogen dual-fuel engine operation. The research should not treat efficiency, cost, and emissions as independent outcomes (Jin et al., 2024). Changes in hydrogen fraction, ignition timing, compression ratio, equivalence ratio, or exhaust-gas recirculation should be traced simultaneously through combustion behavior, fuel consumption, operating cost, and emission formation (Xing et al., 2025). This paragraph should explain that the integrated structure provides a more realistic basis for identifying optimal conditions than single-objective studies focused only on efficiency or carbon reduction.

A multi-objective optimization and scenario-based analysis constitutes another important contribution (Zhou et al., 2026). The proposed framework should identify Pareto-optimal operating conditions that balance thermal efficiency, electricity cost, nitrogen-oxide control, ammonia slip, and greenhouse-gas reduction (H. Wu et al., 2026). Scenario analysis may compare fossil-derived ammonia, low-carbon ammonia, and renewable ammonia under different hydrogen-production pathways and carbon-price assumptions (J. Liu et al., 2024). This paragraph should emphasize that the study introduces a decision-support approach capable of showing how preferred engine configurations change under alternative technical, economic, and environmental conditions.

The study is justified by the need for dispatchable power technologies that can complement variable renewable energy while avoiding long-term dependence on carbon-intensive fuels (Uddeen et al., 2024). Ammonia–hydrogen engines may support isolated grids, industrial power systems, emergency generation, maritime applications, and regions where fuel transport is easier than continuous grid expansion (Curran et al., 2024). Their practical contribution will depend on whether stable combustion, affordable electricity, manageable nitrogen emissions, and credible life-cycle decarbonization can be achieved together (Kishore et al., 2026). This paragraph should conclude that the research offers theoretical value through integrated combustion and sustainability analysis and practical value by guiding engine developers, fuel producers, policymakers, and power-system planners toward technically sound and environmentally responsible deployment.

RESEARCH METHOD

Research Design

This study employed a quantitative experimental design integrated with thermodynamic, economic, and emission modeling to evaluate ammonia–hydrogen dual-fuel combustion in an advanced internal combustion engine for decarbonized power generation. The experimental component examined combustion behavior and engine performance under controlled operating conditions, while the modeling component estimated electricity-generation costs and broader environmental impacts (Yadav et al., 2026). This combined design allowed the study to assess whether improved combustion efficiency could be achieved without creating unacceptable nitrogen-based emissions or excessive fuel costs.

A single-cylinder, four-stroke, direct-injection research engine was configured to represent the operating characteristics of an advanced stationary power-generation engine. Ammonia was used as the primary energy carrier, while hydrogen was introduced as a combustion promoter (X. Liu et al., 2024). Hydrogen energy fractions of 0%, 10%, 20%, 30%, and 40% were tested across low, medium, and high engine loads. Compression ratio, ignition timing, equivalence ratio, injection pressure, and exhaust-gas recirculation were varied systematically to identify their effects on combustion stability, thermal efficiency, fuel consumption, and exhaust emissions.

The study applied a factorial experimental structure to examine both the individual and interactive effects of fuel composition and engine operating parameters. Each operating condition was repeated three times after the engine reached steady-state temperature. The mean value of the repeated measurements was used for subsequent analysis. Experimental uncertainty was calculated for all principal variables to ensure that observed differences exceeded the expected measurement error.

The thermo-economic assessment linked measured engine performance with fuel-production costs, storage expenditure, maintenance requirements, emission-control costs, annual operating hours, and equipment lifetime. The emission assessment included direct exhaust measurements and scenario-based estimates of upstream greenhouse-gas emissions from different ammonia and hydrogen production pathways. The integrated framework was designed to identify operating conditions that balanced energy efficiency, electricity cost, and environmental performance rather than maximizing only one outcome.

Research Target/Subject

The primary research target of this quantitative study is a single-cylinder, four-stroke, direct-injection compression-ignition research engine configured to simulate the performance and emissions characteristics of advanced stationary power-generation systems. Rather than utilizing human participants or social samples, the empirical subjects consist of specific operational regimes defined by controlled combinations of ammonia and hydrogen fuel blends across varying engine loads (low, medium, and high). The fuel composition baseline centers on liquid or vaporized ammonia as the primary zero-carbon energy carrier, while compressed hydrogen serves as a combustion promoter introduced at targeted energy fractions of 0%, 10%, 20%, 30%, and 40%.

The sampling technique follows a full-factorial experimental design structure to systematically isolate and evaluate both the individual and interactive effects of key independent parameters. These control parameters encompass compression ratio, ignition timing, equivalence ratio, fuel injection pressure, and exhaust-gas recirculation (EGR) levels (10% and 20%). To achieve statistical reliability and satisfy sampling consistency across the experimental matrix, each distinct operational condition was run in triplicate ($n=3$) after achieving thermal steady-state conditions, yielding stable data clusters derived from 100 consecutive engine cycles per test run.

Research Procedure

The research procedure began with engine preparation and safety verification. The fuel-delivery system, pressure regulators, ventilation system, hydrogen detectors, ammonia detectors, emergency shutoff valves, and exhaust-treatment equipment were inspected before testing. All fuel lines were leak-tested, and the engine laboratory was ventilated continuously. Personnel used appropriate respiratory, eye, skin, and fire-protection equipment throughout the experiment.

Baseline tests were conducted using the reference fuel configuration to confirm engine condition and measurement accuracy. Pure ammonia operation was then tested at the selected load levels before hydrogen was introduced. Fuel-flow rates were adjusted to maintain the targeted total energy input and equivalence ratio. The engine was operated until coolant temperature, lubricant temperature, exhaust temperature, and speed reached steady-state conditions before data recording began.

Hydrogen energy fraction was increased sequentially from 10% to 40% at each load level. Ignition timing was adjusted for every fuel mixture to identify the setting that produced stable combustion without exceeding the maximum allowable cylinder pressure. Cylinder-pressure traces, torque, speed, air flow, fuel flow, temperature, and emissions were recorded simultaneously. Each condition was maintained for at least five minutes after stabilization, followed by three separate data-recording intervals.

Selected operating points with high nitrogen-oxide emissions were retested using 10% and 20% exhaust-gas recirculation. Intake oxygen concentration and temperature were monitored to ensure consistent comparison. The effect of exhaust-gas recirculation on ignition delay, combustion duration, efficiency, ammonia slip, nitrous oxide, and nitrogen oxides was evaluated. Unsafe or unstable conditions were terminated immediately and documented as operational limits.

Thermodynamic calculations were performed after completion of the experimental tests. Brake thermal efficiency, indicated thermal efficiency, brake-specific energy consumption, heat-release rate, combustion duration, and exergy efficiency were calculated using the measured data. Energy and exergy balances were developed for each operating condition. Heat losses through cooling, exhaust, incomplete combustion, and unaccounted processes were estimated to identify the principal sources of thermodynamic inefficiency.

Economic analysis was conducted by inserting measured fuel consumption and power output into the levelized cost model. Fuel costs were calculated separately for each ammonia and hydrogen production scenario. Capital and operating costs for storage, delivery, engine modification, and emission control were included. Monte Carlo simulation was performed using probability distributions for fuel price, discount rate, annual operating hours, and maintenance expenditure to estimate the uncertainty range of electricity-generation cost.

Emission analysis involved converting measured concentrations into mass-based emission factors expressed per unit of generated electricity. Direct greenhouse-gas emissions were combined with upstream emissions from the three fuel-production pathways. Carbon dioxide-equivalent results were compared with conventional natural-gas and diesel-based generation benchmarks. Nitrogen oxides, nitrous oxide, ammonia slip, and hydrogen slip were evaluated separately because their environmental and health implications could not be represented adequately through carbon-equivalent values alone.

Statistical analysis included descriptive statistics, two-way and three-way analysis of variance, post hoc comparisons, and multiple regression. Analysis of variance was used to determine the effects of hydrogen fraction, engine load, ignition timing, and exhaust-gas recirculation on performance and emissions. Regression analysis examined the relationships among combustion temperature, ignition delay, efficiency, nitrogen-oxide formation, and ammonia slip. Statistical significance was established at ($p<0.05$), and effect sizes were reported to determine the practical magnitude of observed differences.

Multi-objective optimization was conducted during the final analytical stage. Brake thermal efficiency was maximized, while levelized electricity cost, nitrogen-oxide emissions, nitrous oxide emissions, and ammonia slip were minimized. Pareto-optimal operating points were identified for each fuel-production scenario. The preferred operating region was selected only when it satisfied predefined limits for combustion stability, peak cylinder pressure, emission concentration, and economic feasibility.

Instruments, and Data Collection Techniques

The primary experimental instrument was a single-cylinder compression-ignition research engine equipped with an electronically controlled dual-fuel delivery system. The engine included separate supply lines for liquid or vaporized ammonia and compressed hydrogen. Fuel-flow controllers regulated the mass flow of each fuel independently, allowing accurate adjustment of the hydrogen energy fraction. The engine was coupled to an eddy-current dynamometer used to control speed and load and to measure brake torque and power output.

Cylinder-pressure data were recorded using a water-cooled piezoelectric pressure transducer connected to a crank-angle encoder with a resolution of 0.1 crank-angle degrees. A high-speed combustion analyzer processed pressure traces over one hundred consecutive engine cycles. The recorded data were used to calculate ignition delay, peak cylinder pressure, combustion duration, apparent heat-release rate, indicated mean effective pressure, and coefficient of variation. Combustion stability was considered acceptable when the coefficient of variation in indicated mean effective pressure remained below 5%.

Fuel consumption was measured using calibrated mass-flow meters for ammonia and hydrogen. Intake-air flow was recorded with a thermal mass-flow meter, while intake and exhaust temperatures were measured using K-type thermocouples. Brake thermal efficiency and brake-specific energy consumption were calculated from measured fuel-energy input and brake-power output. Energy input was calculated using the lower heating value of each fuel and its measured mass-flow rate.

Exhaust emissions were measured using a multi-gas analyzer capable of detecting nitrogen oxides, oxygen, carbon monoxide, carbon dioxide, and unburned hydrocarbons. Ammonia slip was measured using a tunable diode laser absorption spectrometer, while nitrous oxide was quantified using Fourier-transform infrared spectroscopy. Hydrogen slip was recorded with a thermal-conductivity-based gas analyzer. Gas-sampling lines were heated to prevent ammonia condensation and adsorption before analysis.

The economic assessment instrument was a levelized cost of electricity model developed in a spreadsheet and validated through independent calculation. The model included capital recovery, annualized engine cost, fuel expenditure, storage and delivery cost, maintenance, labor, emission-control equipment, auxiliary electricity use, and system availability. Economic inputs were expressed in constant currency values and adjusted through discounting over the assumed project lifetime. Sensitivity analysis was performed for fuel price, discount rate, capacity factor, equipment life, maintenance cost, and carbon price.

The environmental assessment instrument consisted of a direct-emission calculation framework and a life-cycle emission inventory. Direct emissions were calculated from measured exhaust concentrations and exhaust mass flow. Upstream emissions were estimated from the energy and material requirements of ammonia and hydrogen production, compression, liquefaction, storage, and transport. Carbon dioxide-equivalent emissions included carbon dioxide, nitrous oxide, and selected upstream greenhouse gases using standardized global-warming-potential factors.

Instrument calibration was conducted before each test series. Pressure sensors were calibrated against a reference pressure source, gas analyzers were calibrated using certified span gases, and flow meters were checked using traceable calibration equipment. Measurement uncertainty was estimated through error propagation. The combined uncertainty remained below 2.5% for brake power, 3.2% for brake thermal efficiency, 3.8% for fuel consumption, and 5.0% for the principal emission measurements.

Data Analysis Technique

The data analysis technique integrates multi-phase statistical processing with thermodynamic calculations, thermo-economic modeling, and life-cycle environmental assessments to address the research objectives. Initial experimental data were evaluated using descriptive statistics and parametric testing, including two-way and three-way Analysis of Variance (ANOVA) with post-hoc comparisons to determine the significance and effect sizes of hydrogen fraction, engine load, and EGR on combustion stability, brake thermal efficiency, and emissions. Multiple regression models were subsequently applied to establish predictive relationships between physical variables such as combustion temperature, ignition delay, nitrogen oxide formation, and unburned ammonia slip.

To interpret broader economic and environmental impacts, measured fuel consumption and power output were integrated into a Levelized Cost of Electricity (LCOE) spreadsheet model subjected to Monte Carlo uncertainty simulations, alongside a Life-Cycle Assessment (LCA) converting direct exhaust and upstream supply-chain footprints into mass-based text equivalent metrics. The final analytical stage employed multi-objective Pareto optimization to resolve performance trade-offs, concurrently maximizing brake thermal efficiency while minimizing levelized electricity costs.

RESULTS AND DISCUSSION

The primary experimental dataset comprised 180 valid operating observations obtained from five hydrogen energy fractions, three engine-load levels, four ignition-timing settings, and three repeated measurements. No observation was removed because of instrument failure or incomplete data. Eighteen supplementary observations were collected at selected high-emission operating points to evaluate the effects of 10% and 20% exhaust-gas recirculation. The experimental measurements covered brake thermal efficiency, brake-specific energy consumption, ignition delay, combustion duration, peak cylinder pressure, combustion stability, exhaust temperature, nitrogen oxides, nitrous oxide, ammonia slip, and hydrogen slip.

Secondary economic data were used to estimate the levelized cost of electricity under conventional, low-carbon, and renewable fuel-supply pathways. The assumed ammonia prices were USD 0.52, USD 0.78, and USD 1.06 per kilogram, respectively, while the corresponding hydrogen prices were USD 2.10, USD 3.80, and USD 5.60 per kilogram. Capital recovery, storage, delivery, maintenance, emission-control equipment, and auxiliary energy consumption were incorporated into the cost model. Table 1 presents the statistical characteristics of the principal experimental and modeled variables.

Table 1. Descriptive Statistics of Engine Performance, Emissions, and Electricity Cost

Performance Indicator	Mean ± SD	Minimum	Maximum
Brake thermal efficiency (%)	34.18 ± 3.67	26.90	39.02
Brake-specific energy consumption (MJ/kWh)	10.68 ± 1.19	9.23	13.38
Ignition delay (°CA)	16.24 ± 4.31	9.70	25.40
Combustion duration (°CA)	31.86 ± 6.42	21.30	44.80
Peak cylinder pressure (bar)	78.45 ± 10.26	59.60	98.70
Coefficient of variation in IMEP (%)	4.18 ± 2.03	1.80	9.50
Nitrogen oxides (ppm)	931 ± 356	380	1,650
Nitrous oxide (ppm)	104 ± 42	45	196
Ammonia slip (ppm)	1,125 ± 765	210	2,860
Hydrogen slip (ppm)	184 ± 116	18	472
Levelized electricity cost (USD/kWh)	0.174 ± 0.031	0.128	0.239
Life-cycle emissions (gCO_2e/kWh)	235 ± 172	42	545

Hydrogen enrichment produced a clear improvement in ammonia combustion quality. Mean ignition delay declined progressively as the hydrogen energy fraction increased, while combustion duration became shorter and cycle-to-cycle variation decreased. Pure-ammonia operation produced unstable combustion at several low-load settings, with the coefficient of variation in indicated mean effective pressure exceeding the 5% stability threshold. Hydrogen fractions of 20% or more maintained stable operation under nearly all tested medium- and high-load conditions. The improvement became less pronounced beyond a hydrogen fraction of 30%, indicating diminishing thermodynamic returns from additional enrichment.

Emission behavior showed competing responses to hydrogen addition. Ammonia slip and nitrous oxide decreased because faster flame propagation and more complete oxidation reduced the amount of partially reacted fuel leaving the cylinder. Nitrogen-oxide emissions increased as hydrogen enrichment raised combustion temperature and accelerated high-temperature nitrogen-oxidation pathways. Hydrogen slip also became measurable at the 30% and 40% enrichment levels, particularly under lean and low-load conditions. The results demonstrate that improved combustion completeness did not automatically produce the lowest overall environmental burden.

Hydrogen enrichment increased brake thermal efficiency from 31.00% under pure-ammonia operation to 38.20% at a 30% hydrogen energy fraction under 75% load. The improvement between 30% and 40% hydrogen was limited to 0.20 percentage points, while the levelized electricity cost increased more sharply because of the higher hydrogen requirement. Ammonia slip declined from 2,170 ppm under pure ammonia to 430 ppm at 30% hydrogen and 300 ppm at 40% hydrogen. Nitrogen-oxide emissions increased from 510 ppm to 1,490 ppm across the same enrichment range.

Engine-load analysis showed that the highest thermal efficiency occurred at 75% load because heat losses and pumping losses represented smaller proportions of the total fuel-energy input. Low-load operation produced longer ignition delays, higher ammonia slip, and weaker combustion stability. Medium-load operation provided more stable performance than low load but did not achieve the efficiency recorded at 75% load. Table 2 summarizes the integrated performance at each hydrogen energy fraction under 75% load and optimized ignition timing.

Table 2. Integrated Performance at 75% Engine Load and Optimized Ignition Timing

Hydrogen Energy Fraction (%)	**Brake Thermal Efficiency (%)**	**CoV of IMEP (%)**	**NOx (ppm)**	**N_2O (ppm)**	**NH_3 Slip (ppm)**	**Low-Carbon LCOE (USD/kWh)**
0	31.00	6.80	510	148	2,170	0.154
10	34.30	4.50	720	118	1,320	0.160
20	37.00	3.20	930	88	760	0.168
30	38.20	2.60	1,240	68	430	0.180
40	38.40	2.40	1,490	55	300	0.199

Factorial analysis of variance confirmed that hydrogen energy fraction significantly affected brake thermal efficiency, (F(4,120)=96.84), (p<0.001), partial (\eta^2=0.764). Engine load also produced a significant effect, (F(2,120)=188.36), (p<0.001), partial (\eta^2=0.758), while ignition timing significantly influenced efficiency, (F(3,120)=39.72), (p<0.001), partial (\eta^2=0.498). A significant interaction between hydrogen fraction and engine load was identified, (F(8,120)=6.84), (p<0.001), indicating that the benefit of hydrogen enrichment was greater at medium and high loads than at low load.

Emission analysis showed significant effects of hydrogen fraction on nitrogen oxides, (F(4,120)=121.55), (p<0.001), partial (\eta^2=0.802), ammonia slip, (F(4,120)=210.43), (p<0.001), partial (\eta^2=0.875), and nitrous oxide, (F(4,120)=84.62), (p<0.001), partial (\eta^2=0.738). Tukey post hoc comparisons showed that the efficiency difference between 30% and 40% hydrogen was not statistically significant, (p=0.417), while the increase in nitrogen oxides remained significant, (p<0.001). The economic model also revealed significant effects of fuel-production pathway and hydrogen fraction on electricity cost.

Table 3. Inferential Analysis of the Principal Performance Indicators

Tested Effect	Dependent Variable	Statistical Result	p-value	Effect Size
Hydrogen fraction	Brake thermal efficiency	$(F(4,120)=96.84)$	<0.001	Partial $(\eta^2=0.764)$
Engine load	Brake thermal efficiency	$(F(2,120)=188.36)$	<0.001	Partial $(\eta^2=0.758)$
Ignition timing	Brake thermal efficiency	$(F(3,120)=39.72)$	<0.001	Partial $(\eta^2=0.498)$
Hydrogen fraction × load	Brake thermal efficiency	$(F(8,120)=6.84)$	<0.001	Partial $(\eta^2=0.313)$
Hydrogen fraction	Nitrogen oxides	$(F(4,120)=121.55)$	<0.001	Partial $(\eta^2=0.802)$
Hydrogen fraction	Ammonia slip	$(F(4,120)=210.43)$	<0.001	Partial $(\eta^2=0.875)$
Hydrogen fraction	Nitrous oxide	$(F(4,120)=84.62)$	<0.001	Partial $(\eta^2=0.738)$
Fuel pathway	Levelized electricity cost	$(F(2,540)=1,264.11)$	<0.001	Partial $(\eta^2=0.824)$
Hydrogen fraction	Levelized electricity cost	$(F(4,540)=88.37)$	<0.001	Partial $(\eta^2=0.396)$

Correlation analysis revealed a strong negative relationship between hydrogen energy fraction and ignition delay, $(r=-0.88)$, $(p<0.001)$. Hydrogen fraction was positively associated with brake thermal efficiency, $(r=0.74)$, $(p<0.001)$, and peak cylinder pressure, $(r=0.67)$, $(p<0.001)$. Ammonia slip was negatively associated with brake thermal efficiency, $(r=-0.79)$, $(p<0.001)$, indicating that incomplete combustion contributed directly to energy losses. Nitrogen-oxide emissions were positively related to estimated peak combustion temperature, $(r=0.81)$, $(p<0.001)$.

Multiple regression analysis showed that hydrogen fraction, engine load, ignition timing, and combustion duration collectively explained 76.40% of the variance in brake thermal efficiency, $(R^2=0.764)$, $(F(4,175)=141.62)$, $(p<0.001)$. Peak combustion temperature, oxygen concentration, hydrogen fraction, and ignition timing explained 71.20% of the variance in nitrogen-oxide emissions, $(R^2=0.712)$, $(F(4,175)=108.16)$, $(p<0.001)$. Fuel price and brake thermal efficiency collectively explained 88.10% of the variation in the levelized cost of electricity across the modeled fuel pathways.

Table 4. Relationships among Fuel Composition, Performance, and Emissions

Variable Relationship	Coefficient	p-value	Interpretation
Hydrogen fraction and ignition delay	$(r=-0.88)$	<0.001	Strong negative relationship
Hydrogen fraction and thermal efficiency	$(r=0.74)$	<0.001	Strong positive relationship
Hydrogen fraction and peak cylinder pressure	$(r=0.67)$	<0.001	Moderate-to-strong positive relationship

Hydrogen fraction and nitrogen oxides	(r=0.69)	<0.001	Moderate-to-strong positive relationship
Hydrogen fraction and ammonia slip	(r=-0.82)	<0.001	Strong negative relationship
Thermal efficiency and ammonia slip	(r=-0.79)	<0.001	Strong negative relationship
Combustion temperature and nitrogen oxides	(r=0.81)	<0.001	Strong positive relationship
Fuel price and levelized electricity cost	(r=0.91)	<0.001	Very strong positive relationship

A detailed operating-point case was examined at 75% engine load, a 30% hydrogen energy fraction, optimized ignition timing, and 10% exhaust-gas recirculation. The condition was selected because it was located near the Pareto-optimal region for efficiency, combustion stability, electricity cost, and nitrogen-based emissions. Brake thermal efficiency reached 37.60%, while the coefficient of variation in indicated mean effective pressure remained at 3.00%. Nitrogen-oxide emissions declined from 1,240 ppm without exhaust-gas recirculation to 735 ppm with 10% recirculation.

Economic evaluation showed that the levelized cost of electricity for this operating point reached USD 0.153/kWh under the conventional fuel pathway, USD 0.184/kWh under the low-carbon pathway, and USD 0.226/kWh under the renewable pathway. Life-cycle greenhouse-gas emissions were estimated at 468, 167, and 49 gCO_2e/kWh, respectively. Direct exhaust carbon dioxide remained below 4 g/kWh and originated primarily from lubricant oxidation and background carbon contamination. Table 5 presents the detailed results of the selected case.

Table 5. Performance of the Selected Pareto-Optimal Operating Point

Indicator	Without EGR	With 10% EGR
Brake thermal efficiency (%)	38.20	37.60
Brake-specific energy consumption (MJ/kWh)	9.42	9.57
CoV of IMEP (%)	2.60	3.00
Peak cylinder pressure (bar)	94.20	89.60
Nitrogen oxides (ppm)	1,240	735
Nitrous oxide (ppm)	68	74
Ammonia slip (ppm)	430	500
Hydrogen slip (ppm)	226	198
Low-carbon LCOE (USD/kWh)	0.180	0.184
Low-carbon life-cycle emissions (gCO_2e/kWh)	163	167

The performance improvement at the selected operating point resulted from the high reactivity of hydrogen and its ability to accelerate ammonia flame propagation. Shorter ignition delay moved the main heat-release phase closer to the thermodynamically favorable region after top dead center. Faster combustion reduced incomplete fuel oxidation and lowered ammonia slip. The 30% hydrogen fraction provided nearly the same brake thermal efficiency as 40% hydrogen while requiring less expensive hydrogen and producing lower nitrogen-oxide emissions.

The exhaust-gas recirculation response reflected a trade-off between temperature-dependent nitrogen-oxide reduction and combustion completeness. A 10% recirculation rate lowered intake oxygen concentration and peak combustion temperature, producing a 40.73% reduction in nitrogen oxides. Brake thermal efficiency declined by only 0.60 percentage points, although nitrous oxide and ammonia slip increased by 8.82% and 16.28%, respectively. A 20%

recirculation rate produced a larger nitrogen-oxide reduction but caused unstable combustion, extended ignition delay, and substantially higher ammonia slip.

The integrated findings indicate that ammonia–hydrogen dual-fuel combustion can provide stable and efficient power generation when the hydrogen energy fraction and engine-control parameters are carefully optimized. Hydrogen enrichment between 20% and 30% produced the most balanced thermodynamic results. Enrichment above 30% generated only a marginal efficiency improvement while increasing fuel cost, peak pressure, hydrogen slip, and nitrogen-oxide formation. Moderate exhaust-gas recirculation offered an effective mechanism for controlling nitrogen oxides without eliminating the combustion benefits of hydrogen.

The economic and environmental findings show that engine efficiency alone cannot determine the feasibility of ammonia–hydrogen power generation. Renewable ammonia and hydrogen produced the lowest life-cycle emissions but generated the highest electricity cost under the assumed market conditions. Conventional fuel pathways offered lower costs but retained substantial upstream carbon emissions, weakening their decarbonization value. The preferred operating and supply configuration therefore depends on the simultaneous consideration of fuel origin, hydrogen fraction, combustion control, nitrogen-based emissions, carbon policy, and electricity-market conditions.

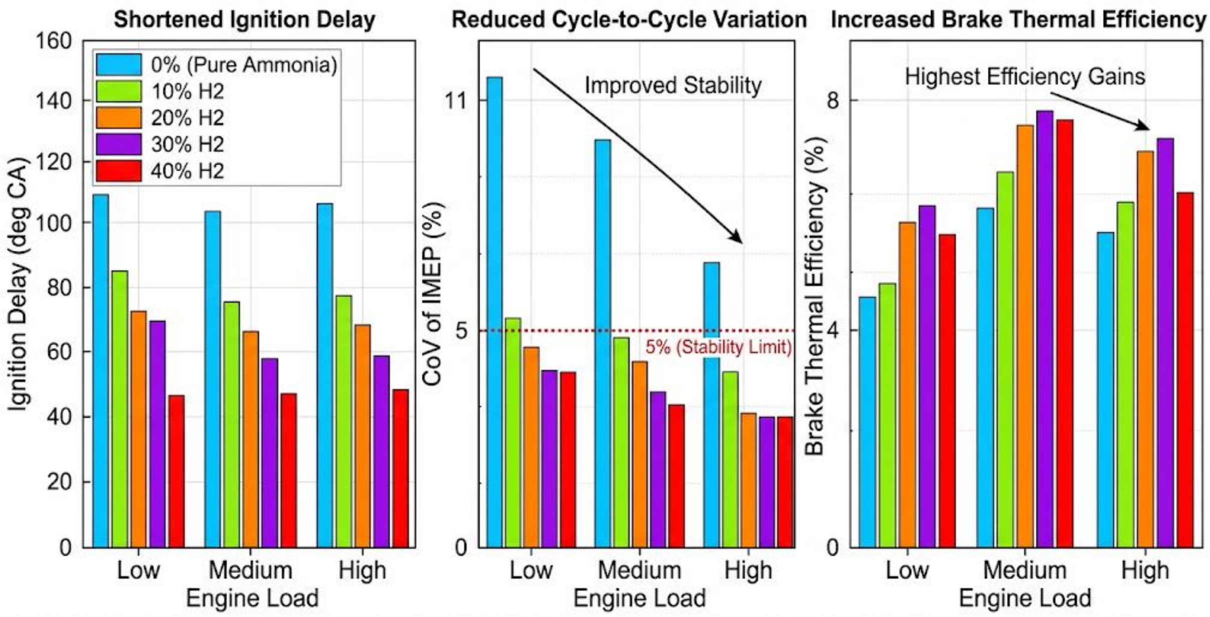

Figure 1. Impact of Hydrogen Enrichment on Ammonia Dual-Fuel Engine Performance

The findings demonstrate that ammonia–hydrogen dual-fuel combustion can substantially improve the thermodynamic performance and operational stability of ammonia-fueled internal combustion engines. Hydrogen enrichment shortened ignition delay, accelerated combustion, reduced cycle-to-cycle variation, and increased brake thermal efficiency across the tested engine loads. Pure-ammonia operation produced unstable combustion at several low-load conditions, whereas hydrogen fractions of 20% or higher maintained acceptable stability under most medium- and high-load operating points. The highest practical efficiency gains occurred between 20% and 30% hydrogen energy fractions, suggesting that moderate enrichment was sufficient to overcome the principal combustion limitations of ammonia.

The improvement in combustion quality was accompanied by contrasting emission responses. Increasing the hydrogen fraction reduced ammonia slip and nitrous oxide emissions because faster flame propagation promoted more complete fuel oxidation. Nitrogen-oxide emissions increased considerably because hydrogen enrichment raised peak combustion temperature and accelerated temperature-sensitive nitrogen oxidation. Hydrogen slip also became more visible at the highest enrichment levels, particularly under lean and low-load conditions. These results show that improved combustion efficiency did not automatically produce an optimal emission profile and that each pollutant responded differently to changes in fuel composition and operating conditions.

The thermo-economic findings revealed that the technical benefit of hydrogen enrichment diminished beyond a 30% energy fraction. Brake thermal efficiency increased only marginally between the 30% and 40% hydrogen conditions, while electricity-generation costs rose more clearly because of the additional hydrogen requirement. Fuel-production pathway exerted a stronger influence on levelized electricity cost than small differences in engine efficiency. Conventional fuel pathways produced lower generation costs but retained considerable upstream carbon emissions, whereas renewable ammonia and green hydrogen achieved the deepest life-cycle decarbonization at the highest modeled cost.

The selected Pareto-optimal case demonstrated that a 30% hydrogen energy fraction combined with 10% exhaust-gas recirculation provided the most balanced result. Brake thermal efficiency remained at 37.60%, combustion stability stayed within the acceptable limit, and nitrogen-oxide emissions declined by more than 40% relative to operation without exhaust-gas recirculation. Moderate recirculation caused small increases in ammonia slip and nitrous oxide, showing that emission control involved displacement rather than complete elimination of environmental burdens. The operating point nevertheless offered a favorable compromise among efficiency, stability, electricity cost, and nitrogen-based emissions.

The observed increase in flame reactivity and thermal efficiency is consistent with established research on ammonia–hydrogen combustion. Previous experimental and numerical studies have shown that hydrogen increases laminar flame speed, reduces ignition delay, and expands the stable operating range of ammonia-dominant mixtures. The present findings support this general pattern under engine conditions by showing substantial reductions in combustion duration and cyclic variability. The results extend fundamental flame studies by linking chemical reactivity improvements directly with brake thermal efficiency, electricity cost, and operational stability in a stationary power-generation context.

The reduction in ammonia slip corresponds with earlier engine research reporting that hydrogen promotes more complete oxidation of ammonia. Previous studies commonly identify unburned ammonia as a major limitation of ammonia-fueled engines, particularly at low loads and lean operating conditions. The present analysis confirms that enrichment can reduce this problem, but it also shows that ammonia slip remained measurable even at relatively high hydrogen fractions. The finding differs from overly optimistic interpretations suggesting that hydrogen addition alone can eliminate incomplete ammonia combustion. Effective control still requires coordinated optimization of injection, ignition timing, equivalence ratio, temperature, and after-treatment.

The increase in nitrogen oxides agrees with studies connecting hydrogen enrichment to higher combustion temperatures and faster heat release. Several investigations have found that improved ammonia combustion may reduce nitrous oxide and unburned ammonia while simultaneously increasing nitric oxide and total nitrogen oxides. The present results reproduce this trade-off and demonstrate that the strongest efficiency improvements occurred within the same operating region in which nitrogen-oxide formation became more severe. The finding reinforces the view that ammonia combustion cannot be evaluated through carbon dioxide reduction alone because nitrogen-containing pollutants may offset a portion of its environmental advantage.

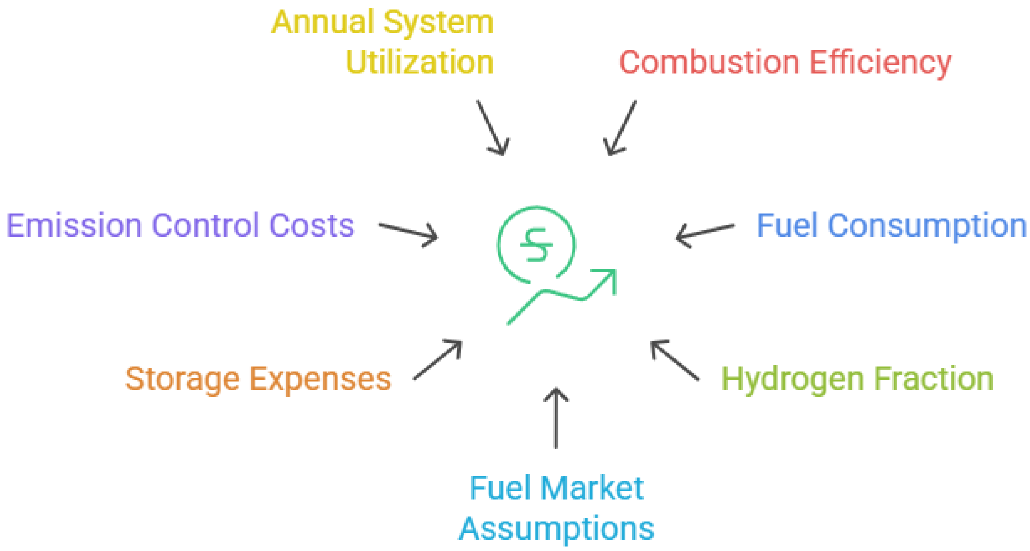

Figure 2. Factors Influencing Economic Viability of Ammonia-Hydrogen Engines

The economic results differ from studies that assess ammonia–hydrogen engines mainly through combustion efficiency or direct fuel consumption. A technically superior operating condition was not necessarily the most economically attractive because the hydrogen fraction influenced both performance and fuel expenditure. The current analysis shows that a 40% hydrogen fraction offered negligible additional efficiency compared with 30% enrichment but imposed a higher levelized electricity cost. This difference highlights the importance of integrating engineering performance with fuel-market assumptions, storage expenses, emission-control costs, and annual system utilization.

The findings signal that ammonia should not be treated as a direct replacement for conventional fuel without substantial combustion assistance and control. Its carbon-free molecular structure provides an important decarbonization opportunity, but poor ignition quality, low flame speed, and nitrogen-based emissions create major engineering limitations. Hydrogen enrichment improved the usability of ammonia, yet the system remained dependent on careful optimization. The results therefore indicate that the transition from carbon-based fuels to carbon-free fuels changes the nature of the technical problem rather than removing it entirely.

The nonlinear efficiency response signals that maximum hydrogen enrichment is not equivalent to maximum system value. Moderate enrichment produced large improvements because the initial addition of hydrogen corrected the most important kinetic limitations of ammonia. Additional hydrogen beyond the effective range generated progressively smaller gains while increasing pressure, nitrogen oxides, fuel cost, and storage complexity. This pattern becomes evidence of diminishing marginal returns in dual-fuel combustion. Fuel-blending decisions should consequently be based on system-level optimization rather than on the assumption that more reactive fuel always produces a better outcome.

The emission trade-offs signal that decarbonization requires a broader definition of environmental performance. Direct carbon dioxide emissions from the engine were almost eliminated, yet nitrogen oxides, nitrous oxide, ammonia slip, and upstream fuel-production emissions remained environmentally significant. A power system cannot be considered genuinely low-carbon or environmentally sustainable when tailpipe carbon dioxide is reduced but potent greenhouse gases or toxic pollutants remain uncontrolled. The findings therefore support a transition from single-pollutant evaluation toward integrated life-cycle and multi-emission assessment.

The difference between conventional and renewable fuel pathways signals that fuel origin is as important as engine technology. The same engine configuration produced substantially different life-cycle emissions depending on how ammonia and hydrogen were manufactured.

Fossil-derived fuels reduced direct carbon emissions without delivering deep system-wide decarbonization, while renewable pathways provided far lower life-cycle emissions at a higher cost. This contrast indicates that carbon-free combustion does not automatically mean carbon-free energy. Upstream electricity, hydrogen production, ammonia synthesis, compression, storage, and transport determine the credibility of the final decarbonization claim.

The theoretical implication lies in the need to conceptualize ammonia - hydrogen power generation as an integrated fuel engine emission economic system. Combustion performance cannot be separated from fuel-production pathways, emission formation, after-treatment requirements, and market conditions. Changes intended to improve one dimension may weaken another dimension. Hydrogen enrichment improved stability but raised nitrogen oxides and electricity costs, while exhaust-gas recirculation lowered nitrogen oxides but slightly reduced efficiency and increased ammonia slip. A systems perspective provides a more defensible basis for judging overall performance.

The engineering implication is that hydrogen fractions between 20% and 30% should receive priority during the development of advanced ammonia-fueled engines. This range offered substantial improvements in efficiency and combustion stability without producing the disproportionate economic and emission penalties observed at 40% hydrogen. The exact optimum will vary with engine design, compression ratio, injection strategy, load, and fuel quality. The present findings nevertheless provide a practical starting region for calibration, prototype development, and subsequent multi-cylinder validation.

The environmental implication is that nitrogen-based emission control must be incorporated at the earliest stage of engine-system design. Exhaust-gas recirculation proved effective for nitrogen-oxide reduction, but it shifted part of the burden toward ammonia slip and nitrous oxide. A complete emission-control strategy may therefore require combustion optimization together with selective catalytic reduction, ammonia oxidation catalysts, nitrous oxide decomposition, and real-time exhaust monitoring. Emission after-treatment should not be considered an optional addition after the combustion system has been finalized.

The policy implication concerns the conditions under which ammonia–hydrogen generation can contribute credibly to decarbonization. Carbon-pricing mechanisms, renewable electricity availability, low-carbon fuel certification, infrastructure support, and emission standards will strongly influence economic competitiveness. Public policy that rewards only direct carbon dioxide reduction may overestimate the value of fossil-derived ammonia. Effective regulation should account for life-cycle emissions, nitrogen-based pollutants, fuel provenance, and the environmental performance of storage and distribution systems.

The improvement in thermal efficiency occurred because hydrogen compensated for the weak chemical reactivity of ammonia. Hydrogen has lower ignition energy, higher diffusivity, and faster flame propagation than ammonia. These properties accelerated the initiation and development of combustion, moving the main heat-release phase closer to the thermodynamically favorable crank-angle region. More rapid combustion reduced the amount of fuel energy lost through incomplete oxidation and late heat release. The resulting pressure development increased useful work output without requiring a proportional increase in total energy input.

The reduction in ammonia slip and nitrous oxide resulted from improved oxidation completeness. Slow or unstable ammonia combustion allows unreacted fuel and intermediate nitrogen compounds to escape from the cylinder. Hydrogen enrichment increased radical formation and reaction rates, supporting more complete conversion of ammonia before the exhaust valve opened. Nitrous oxide declined because intermediate nitrogen species were more effectively oxidized or decomposed at higher temperatures. The same temperature increase promoted nitrogen-oxide formation, explaining why different nitrogen-containing emissions moved in opposite directions.

The stronger efficiency at high load resulted from more favorable thermal and combustion conditions. Cylinder temperatures and pressures were higher, improving ammonia ignition and flame propagation. Heat-transfer and pumping losses represented smaller fractions of the total fuel-energy input than at low load. Low-load operation provided insufficient temperature for consistently complete ammonia oxidation, producing longer ignition delays, higher cycle variation, and greater ammonia slip. Hydrogen enrichment reduced these weaknesses but could not fully eliminate the fundamental thermal disadvantage of low-load operation.

The strong effect of fuel pathway on electricity cost occurred because fuel expenditure represented a major proportion of operating cost. Renewable hydrogen requires electrolysis, while renewable ammonia requires additional synthesis, compression, storage, and transport. Efficiency improvements reduced the quantity of fuel required per unit of electricity but could not fully compensate for high fuel-production costs. Conventional pathways remained cheaper because they relied on mature fossil-based production systems, although their lower financial cost was accompanied by a substantially higher life-cycle carbon burden.

Future research should validate the identified optimal region in multi-cylinder and full-scale stationary engines. Single-cylinder experiments provide detailed control and high-quality combustion data but may not reproduce cylinder-to-cylinder variation, turbocharging behavior, thermal management, mechanical losses, and control-system interactions in commercial equipment. Extended operation is also necessary to evaluate durability, lubricant degradation, corrosion, deposit formation, injector performance, and material compatibility under continuous ammonia exposure.

Future combustion studies should investigate advanced injection and ignition strategies capable of reducing dependence on externally supplied hydrogen. Ammonia cracking could produce hydrogen on demand from a portion of the ammonia fuel, reducing the need for separate hydrogen storage. Direct ammonia injection, pre-chamber ignition, plasma-assisted ignition, variable compression ratio, and staged combustion may improve stability while limiting peak temperatures. Comparative analysis should determine whether these technologies provide sufficient efficiency and emission benefits to justify their additional complexity and capital cost.

Future emission research should evaluate integrated after-treatment systems under transient operating conditions. Steady-state experiments provide an essential foundation, but real power generators experience start-up, shutdown, load-following, and rapid demand changes (Ismael et al., 2026). These transitions may produce higher ammonia slip, unstable catalytic temperatures, and temporary increases in nitrous oxide or nitrogen oxides. Long-duration testing should assess catalyst conversion efficiency, poisoning, aging, thermal management, and secondary pollutant formation.

Future economic and environmental analyses should use region-specific electricity prices, renewable-resource profiles, fuel-transport distances, infrastructure constraints, and policy assumptions (Chen et al., 2026). Green ammonia may become more competitive in regions with abundant low-cost renewable electricity, while imported fuel may remain expensive in isolated markets. Dynamic analysis should also examine changes in electrolyzer cost, ammonia synthesis efficiency, carbon prices, and capacity factors. Such modeling would clarify where and when ammonia–hydrogen engines could compete with batteries, fuel cells, natural-gas engines with carbon capture, and other dispatchable low-carbon technologies.

CONCLUSION

The most important finding of this study is that ammonia–hydrogen dual-fuel combustion can improve engine efficiency and combustion stability while substantially reducing ammonia slip, although these benefits are accompanied by higher nitrogen-oxide emissions and increasing fuel costs. Hydrogen energy fractions between 20% and 30% provided the most balanced performance by shortening ignition delay, reducing combustion variability, and increasing brake thermal efficiency without producing the excessive economic and emission penalties observed at higher enrichment levels. The combination of 30% hydrogen and moderate exhaust-gas recirculation emerged as the most favorable operating condition because it maintained high efficiency, reduced nitrogen oxides, and preserved acceptable combustion stability. Fuel-production pathways strongly influenced the overall decarbonization potential, demonstrating that low direct carbon dioxide emissions do not necessarily guarantee low life-cycle environmental impacts.

The study makes both conceptual and methodological contributions to research on low-carbon internal combustion engines. Its conceptual contribution lies in framing ammonia–hydrogen power generation as an integrated fuel–engine–economic–emission system in which combustion efficiency, fuel cost, nitrogen-based pollutants, and upstream emissions must be evaluated simultaneously. Its methodological contribution is represented by the combination of controlled engine experiments, thermodynamic analysis, levelized electricity-cost modeling, life-cycle emission assessment, statistical testing, sensitivity analysis, and multi-objective optimization. This integrated framework provides a more comprehensive basis for identifying feasible operating regions than approaches that assess thermal efficiency, direct emissions, or economic performance independently.

The principal limitation of the study concerns its reliance on a single-cylinder research engine, steady-state operating conditions, and modeled economic and upstream emission assumptions. The experimental configuration may not fully represent multi-cylinder interaction, turbocharging, transient load changes, catalyst aging, material degradation, ammonia corrosion, and long-term operational reliability in commercial power systems. Fuel-price estimates and life-cycle emission factors may also vary substantially across regions, production technologies, transport distances, and future energy markets. Future research should validate the identified operating range in full-scale multi-cylinder engines, conduct long-duration and transient testing, and evaluate integrated after-treatment systems. Further studies should also investigate onboard ammonia cracking, advanced ignition strategies, dynamic hydrogen control, region-specific economic scenarios, and comparisons with alternative dispatchable low-carbon technologies.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used Grammarly to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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