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Research Article

Improving Engine Efficiency Using Hydrogen-Assisted Combustion: Experimental Testing and Machine-Learning Prediction

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ABSTRACT

This study investigates the performance enhancement and emission reduction potential of a gasoline internal combustion engine using on-demand hydrogen (HHO) enrichment generated through alkaline electrolysis. Unlike studies relying on compressed hydrogen storage, the proposed system produces hydrogen in real time and injects it into the intake manifold, eliminating storage risks and reducing system complexity. Experimental testing was conducted on a 2.4-L spark-ignition engine using a chassis dynamometer and OBD-II data acquisition. Engine operation was evaluated under two conditions: baseline gasoline mode and hydrogen-assisted gasoline mode. Key performance metrics included power output, torque, fuel consumption, air–fuel ratio (AFR), and exhaust emissions (CO_2, CO, HC, and NOx). Results showed that hydrogen enrichment significantly improved combustion characteristics. Maximum power increased from 99.47 hp to 121.47 hp (+22.14%), and maximum torque rose from 96.34 ft-lb to 131.90 ft-lb (+36.9%). At steady-state cruising, fuel consumption decreased from 8.56 L/h to 7.23 L/h (−15.53%), with AFR shifting from 15.1:1 to 15.5:1, confirming lean-burn operation. Emissions of CO_2, CO, HC, and NOx decreased due to faster flame propagation and more complete oxidation.

To complement the experimental results, regression modeling and an artificial neural network (ANN) soft sensor were developed to predict engine power and fuel rate based on hydrogen flow rate and RPM. The regression model achieved an R^2 of 0.999 for fuel prediction, while the ANN achieved an R^2 of 0.959 for power prediction, demonstrating strong predictive capability and applicability for real-time decision support. The findings demonstrate that hydrogen enrichment is a technically and economically viable approach to improving engine efficiency and reducing emissions, offering an immediate transitional pathway toward sustainable mobility without requiring major engine modifications.

Keywords: Hydrogen-assisted combustion; Internal combustion engine; Brown's gas (HHO); Emission reduction; Soft sensor; Fuel efficiency; Water electrolysis

INTRODUCTION

Hydrogen has gained increasing attention as a clean and sustainable energy vector due to its zero-carbon combustion characteristics and high energy content per unit mass (Hosseini & Wahid, 2021). Fossil fuels emit CO_2 and other pollutants during combustion, whereas hydrogen reacts with oxygen to produce only water vapor (Zuttel et al., 2019). As global climate targets intensify and emission reduction regulations become stricter, hydrogen is positioned as a viable transition fuel for the transportation sector (International Energy Agency, 2023). In addition, hydrogen can be sourced from renewable energy via electrolysis, reducing reliance on fossil-based hydrogen production pathways (Hosseini & Wahid, 2021).

Hydrogen has exceptional combustion characteristics, with a flame speed of 2.065 m/s, a wide flammability range (4–75%), and low minimum ignition energy. These properties enable lean-burn combustion, improving efficiency and reducing fuel consumption (Verhelst et al., 2020a, 2020b; Verhelst & Wallner, 2009; White et al., 2006b, 2006a).

Because gasoline does not fully oxidize during combustion, CO and HC are produced. Hydrogen addition compensates for this weakness, enabling more complete oxidation (Swain & Swain, 1999). Electrolysis splits water into hydrogen and oxygen in a 2:1 ratio. Studies show that electrolysis efficiency increases when using stainless-steel electrodes and NaOH electrolyte (Peters et al., 2024). Pulse-width modulation (PWM) improves reaction efficiency (Sabzehali et al., 2022). HHO (Brown's gas) is combustible and increases flame propagation inside the cylinder, allowing smaller gasoline injections while maintaining power output (Tang & Ouyang, 2012). Recent studies demonstrate the following performance outcomes (**Table 1**):

Table 1. Studies of Performance Outcomes

Study	**Performance Outcome**
Yilmaz (2022)	Increase in torque from 10–20%
Li et al. (2022)	Increase BTE, increasae in CO_2 of 40%
Hosseini & Wahid (2021)	Hydrogen as transition technology
Kawasaki & Ogawa (2005)	DI hydrogen improved thermal efficiency

LITERATURE REVIEW

Hydrogen consistently increases brake thermal efficiency (BTE) due to improved combustion completeness. Most studies examine hydrogen-cylinder fueling systems, not on-demand electrolysis and laboratory setups, and not real vehicle road testing. There is limited analysis on economic feasibility. This study, with the support of the regression and ANN models, contributes by using a real automotive platform and calculating fuel savings and ROI, aligning with industry applicability. The investigation of hydrogen as an engine fuel began in the 1970s when researchers explored spark ignition hydrogen engines due to fuel shortages (Homan & Hung, 1978). Early studies demonstrated that hydrogen engines achieved complete combustion and drastically lower emissions than gasoline engines (Furuhama & Fukuma, 1986; Nayak et al., 2025; Swain & Swain, 1999; Wojs Marcin Krzysztof and Laskowski, 2025; Zbikowski & Teodorczyk, 2025; Zhang et al., 2025). These foundational works established that hydrogen had superior flame speed, higher diffusivity, and required lower ignition energy compared to gasoline (Verhelst et al., 2020a, 2020b; Verhelst & Wallner, 2009).

Subsequent research examined the feasibility of hydrogen–gasoline hybrid combustion, in which hydrogen does not replace gasoline but supplements it. Lee et al. (2010) confirmed that even small hydrogen percentages improve combustion characteristics and reduce unburnt hydrocarbons (HC) and carbon monoxide (CO) (Lee et al., 2010). Tang and Ouyang (2012) reviewed hydrogen use in spark-ignition engines and concluded that hydrogen allows engines to operate at leaner air–fuel ratios while maintaining or increasing thermal efficiency (Tang & Ouyang, 2012). Hydrogen's combustion properties provide significant benefits when introduced into gasoline engines, as shown in **Table 2.**

Table 2. Performance Benefit based on Property (Verhelst & Wallner, 2009; White et al., 2006b, 2006a)

Property	**Performance Benefit**
Extremely low ignition energy (0.02 mJ)	Enables faster flame initiation
High flame speed (2.065 m/s)	Increases combustion completeness
Wide flammability range (4–75% in air)	Supports lean-burn efficiency
Diffusion coefficient 4–5× higher than gasoline vapor	Improves mixing and fuel–air homogeneity

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Hydrogen reduces ignition delay, which improves cycle uniformity, thereby delivering smoother torque and power characteristics (Kawasaki & Ogawa, 2005). In dual-fuel mode, hydrogen displaces gasoline during combustion, reducing the amount of gasoline injected into the chamber without compromising performance (Saravanan et al., 2008).

Hydrogen Production via Water Electrolysis (HHO / Brown's Gas)

Hydrogen can be produced using water electrolysis:

$$2H_2O \rightarrow 2H_2 + O_2 \quad (1)$$

HHO (Brown's gas) is a stoichiometric mixture of hydrogen and oxygen produced by electrolysis and burned together at the point of use. Electrolysis efficiency depends on electrode material, electrolyte concentration, and power input (Das, 1991). Stainless steel plates (SS316L) are widely used due to corrosion resistance (Peters et al., 2024). Sabzehali et al. (2022) demonstrated that modulated power delivery using pulse-width modulation (PWM) increases gas generation rate while reducing heat loss in the electrolysis cell (Sabzehali et al., 2022). HHO-assisted engines exhibit improved thermal efficiency because HHO promotes faster flame propagation and complete oxidation (Das, 1991; Verhelst et al., 2020a, 2020b).

Many studies confirm that adding hydrogen increases torque and horsepower. Yilmaz (2022) recorded a 10–20% torque improvement in hydrogen-assisted gasoline engines. Kawasaki and Ogawa (2005) achieved improved flame acceleration in direct-injection hydrogen engines (Kawasaki & Ogawa, 2005). Hosseini and Wahid (2021) emphasized hydrogen's role in improving efficiency during partial-load operation (Hosseini & Wahid, 2021). Hydrogen also improves brake thermal efficiency (BTE) because combustion becomes more complete. Li et al. (2022) demonstrated that hydrogen improves engine thermal efficiency and reduces CO_2 emissions up to 40%, especially under lean conditions (Li et al., 2022).

Emission Reduction Potential

Hydrogen addition reduces CO and HC emissions due to increased combustion completeness (Das, 1991; Saravanan et al., 2008). Reducing CO_2 emissions occurs when hydrogen displaces gasoline during combustion (Li et al., 2022). NOx emissions reduce when paired with EGR or lean-burn mode (Lee et al., 2010; Miyamoto & Ogawa, 2000). Szwaja and Grab-Rogalinski (2009) tested hydrogen combustion in spark ignition engines and reported significantly lower HC and CO, confirming that the presence of hydrogen minimizes incomplete oxidation (Szwaja & Grab-Rogalinski, 2009).

Despite promising research, most prior studies use compressed hydrogen tanks, posing storage and safety challenges. On the other hand, the focus is on laboratory bench engines and not on real vehicles. Few studies evaluate engine performance in real driving conditions. Even fewer predict it through ANN soft sensing. Emission measurements will be calculated across multiple RPM loads. Economic feasibility (cost–benefit analysis) will also be considered in this study. The current experiment addresses these gaps by generating hydrogen on demand (no tank storage) and integrating HHO into a commercial vehicle. Quantifying emissions, torque, horsepower, efficiency, and ROI experimentally and through modeling. Thus, the study advances hydrogen-enhanced ICE research from feasibility to practical applicability.

DESIGN AND EXECUTION

This section describes the experimental procedures used to design, integrate, and evaluate the hydrogen-assisted gasoline combustion system. The methodology consisted of three stages: 1) design and fabrication of the hydrogen generation system, 2) engine integration and calibration, and 3) performance, fuel consumption, and emission testing. A quantitative experimental research design was used, comparing engine performance and emissions under two controlled conditions: 1) baseline condition (gasoline only) and 2) hydrogen-assisted condition (gasoline + HHO gas injection). The experiment was conducted on a 2008 Toyota Camry with a 2.4-L spark-ignition engine, without internal mechanical modifications. Hydrogen was not stored; it was generated on-demand through alkaline water electrolysis. The independent variable was hydrogen enrichment. The dependent variables were 1) Engine performance (horsepower, torque), 2) Brake thermal efficiency, 3) Fuel consumption (L/h and L/100 km), and 4) Exhaust emissions (CO_2, CO, HC, NOx, and O_2).

Hydrogen Generation System (HHO Electrolysis Unit)

A custom HHO generator was fabricated to produce a stoichiometric mixture of hydrogen and oxygen (Brown's gas) using alkaline electrolysis. Key system components, as shown in **Table 3**, included:

Table 3. Ket System Components

Component	**Specification**
Electrolysis cell	Stainless steel SS316L parallel plates (corrosion-resistant)
Electrolyte	NaOH solution (enhances water conductivity)
Power supply	30 V – 75 A DC regulated using Pulse Width Modulation (PWM)
Gas drying and safety	Water bubbler + flame arrestor + non-return valve
Gas sensor	MQ-8 hydrogen leak detector near intake manifold

Using PWM minimized heat buildup and prevented electrode degradation, and improving hydrogen generation efficiency was implemented, which is an approach consistent with Sabzehali et al. (2022) and Peters et al. (2024). Hydrogen production rate was quantified by measuring gas output (L/min) against applied current and voltage (Peters et al., 2024; Sabzehali et al., 2022). Data confirmed a proportional relationship where higher power (voltage time current) is a reflection on the higher production flow rate.

Hydrogen Injection and Engine Integration

Hydrogen gas from the HHO generator was routed through the bubbler and flame arrestor and injected into the engine intake manifold upstream of the throttle body. This ensured uniform mixing of hydrogen with the intake air. Key control considerations were identified:

- A/F ratio regulation: The ECU automatically adjusted fuel injection.
- Knock prevention: Hydrogen volumetric flow was calibrated to avoid excessively lean mixtures (>18:1).
- EGR adjustment: The engine's internal exhaust gas recirculation (EGR) helped suppress NOx spikes.

Idle-to-medium load injection ensured stable combustion, aligning with prior studies where hydrogen addition improves combustion speed while maintaining safety (Li et al., 2022; White et al., 2006b, 2006a). The air–fuel ratio varied as shown in **Table 4**.

Table 4. Air-Fuel Ratio based on the Operating Mode

Operating Mode	**A/F Ratio**
Gasoline only	15.1 : 1
With hydrogen injection	15.5 : 1 (leaner mixture)

Hydrogen's high diffusivity and fast flame propagation enable stable power output even under lean burn conditions (Verhelst & Wallner, 2009). Three categories of measurements were collected during testing (performance, fuel consumption, and emissions), using the instrumentation below (**Table 5**). Each test was performed three times, and average values were recorded to reduce variability.

Table 5. Measurement Category and Instrumentation

Measurement Category	**Instrumentation Used**
Engine power & torque	Dynojet chassis dynamometer

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Fuel consumption	OBD-II ECU data logging (ELM327 reader)
Emissions (CO_2, CO, HC, NOx, O_2)	Exhaust Gas Analyzer

Performance testing was done using a Dynojet dynamometer in wide-open throttle (WOT) runs. Two runs were conducted: 1) gasoline only and 2) hydrogen-assisted combustion. For each run, horsepower (hp) and torque (ft.lb) were recorded as a function of engine speed (RPM). The observed phenomena shown in **Figure 1** to **Figure 3** drives towards the reduction in power fluctuation that results in smoother combustion, as well as an increase in maximum torque due to faster flame speed and higher brake thermal efficiency (BTE).

Fuel Consumption Testing

Fuel consumption was monitored using OBD-II ECU readings at a constant cruising speed (~81 km/h) and equal road conditions. The test conditions for gasoline only were a fuel consumption of 8.56 L/h, whereas for gasoline with hydrogen, it was 7.23 L/h. Fuel savings were calculated (see **Figure 4** and **Figure 5**):

$$\text{Fuel Reduction (\%)} = \frac{FC_{before} - FC_{after}}{FC_{before}} \times 100 \qquad (2)$$

Emissions were measured at fixed RPM intervals (1000, 1400, 1800, and 2200 RPM). The units used in the parameter measures are shown in **Table 6**. Cost–benefit analysis was performed comparing annual fuel savings to the cost of constructing the electrolysis system (see **Table 7**).

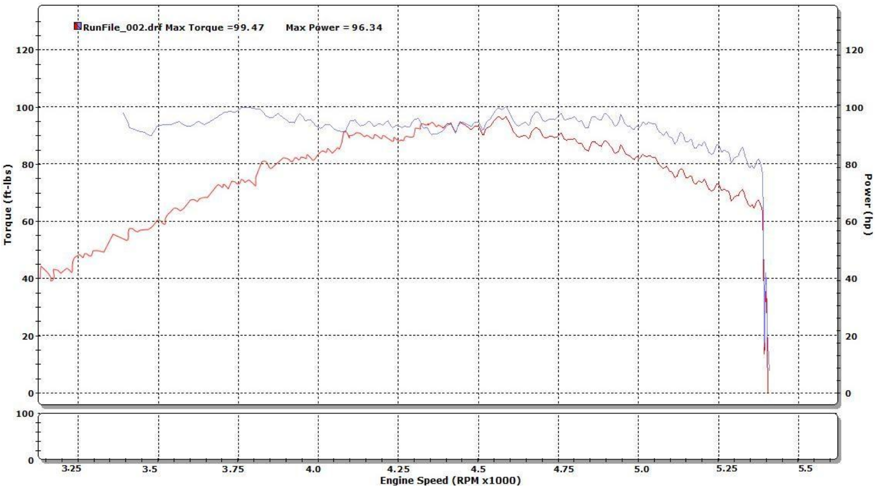

Figure 1. Power & Torque Curve – Baseline

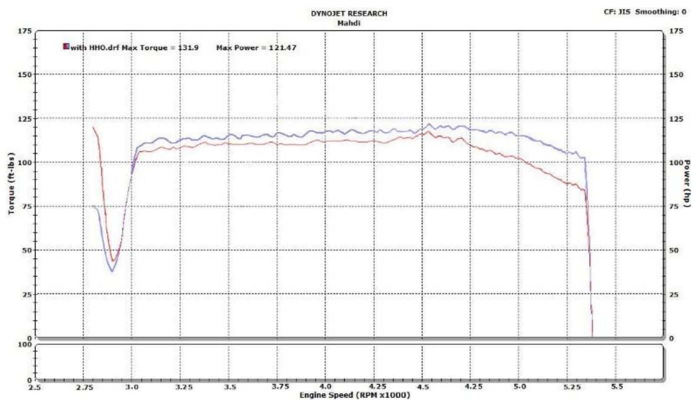

Figure 2. Power & Torque Curve – With Hydrogen

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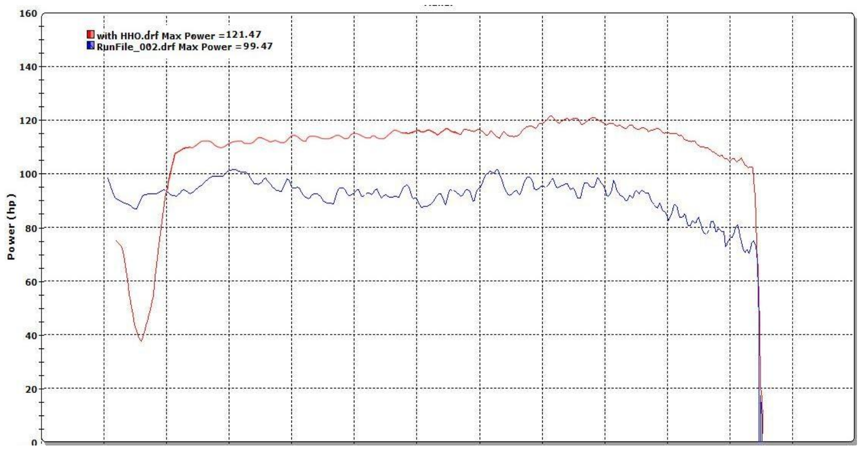

Figure 3. Engine Power Comparison

Table 6. Parameters measured and their units

Parameter Measured	Unit
CO_2	%
CO	%
HC	ppm
NOx	ppm
O_2	%

Table 7. Cost-Benefit Analysis

HHO System Component	Cost (USD)
Electrolysis cell + Power supply	~$300
Estimated annual fuel savings	$250–$300
Return on investment (ROI)	~1 year

In addition to physical experimentation, a data-driven artificial neural network (ANN) model was developed to predict engine performance and estimate combustion efficiency as a function of hydrogen flow rate and engine speed (RPM). The objective of the ANN soft sensor was to establish a predictive model capable of estimating power output and fuel consumption without the need for continuous dynamometer or OBD-II measurements. The experimental dataset collected from dynamometer runs and fuel-rate monitoring was preprocessed into a long-format table containing the variables: engine speed (RPM), hydrogen flow rate (L/min), measured power (hp), torque (ft-lb), and fuel rate (L/h). Inputs to the ANN were RPM (normalized) and hydrogen flow, while outputs were power and fuel rate, representing direct measures of energy conversion and efficiency.

The ANN was implemented using a feed-forward multilayer perceptron (MLP) architecture with two hidden layers, trained using the Adam optimization algorithm. The dataset was randomly divided into 70% training, 15% validation, and 15% testing sets to prevent overfitting and ensure generalization. Model performance was evaluated using the coefficient of determination (R^2) and root mean square error (RMSE). After training, the ANN soft sensor achieved $R^2 = 0.959$ for power prediction and $R^2 = 0.974$ for fuel-rate prediction, indicating a strong agreement between predicted and measured values. The trained ANN was subsequently used to generate prediction surfaces and efficiency maps, enabling simulation of engine behavior under different hydrogen enrichment conditions without requiring further physical tests.

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RESULTS AND DISCUSSIONS

This section presents results obtained from the hydrogen-assisted combustion experiment and discusses their implications relative to prior research. The evaluation focuses on hydrogen production performance, engine performance (power and torque), fuel consumption and combustion efficiency, emissions behavior, and economic feasibility. All tests were performed twice under baseline gasoline operation and hydrogen-assisted gasoline operation, allowing direct comparative analysis.

Hydrogen production was measured as a function of power input to the electrolysis cell. Increasing supply voltage and current increased hydrogen output proportionally, consistent with Faraday's electrochemical law and findings from (Das, 1991; Peters et al., 2024). At maximum operating conditions (30 V, 75 A), hydrogen output reached 3.5 L/min, sufficient to meaningfully enrich the engine intake airflow. Higher hydrogen flow increases the combustion flame speed, enabling more complete oxidation and reducing cycle-to-cycle variation (Verhelst & Wallner, 2009).

Hydrogen enrichment resulted in a substantial improvement in engine power and torque. Dynamometer test results showed that hydrogen-assisted combustion increased. The maximum horsepower increased from 99.45 hp to 121.47 hp (+22.14%), and the maximum torque increased from 96.34 ft-lbs to 131.90 ft-lbs (+36.9%).

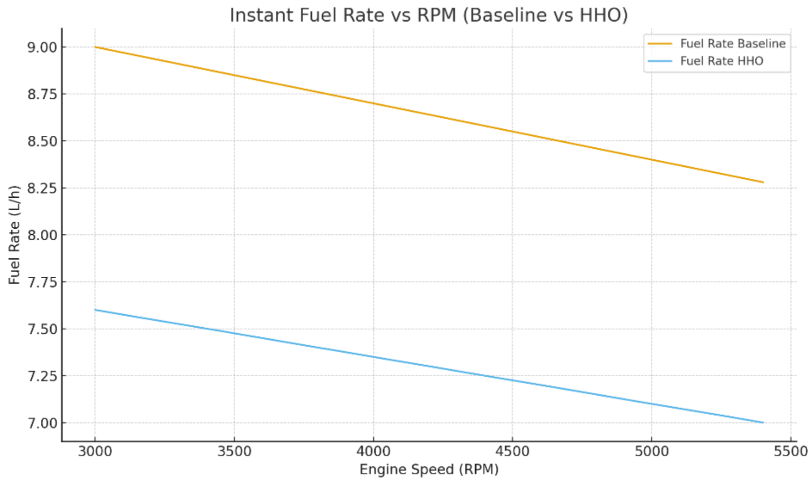

Figure 7. Instant Fuel Rate vs. Engine Speed — Baseline

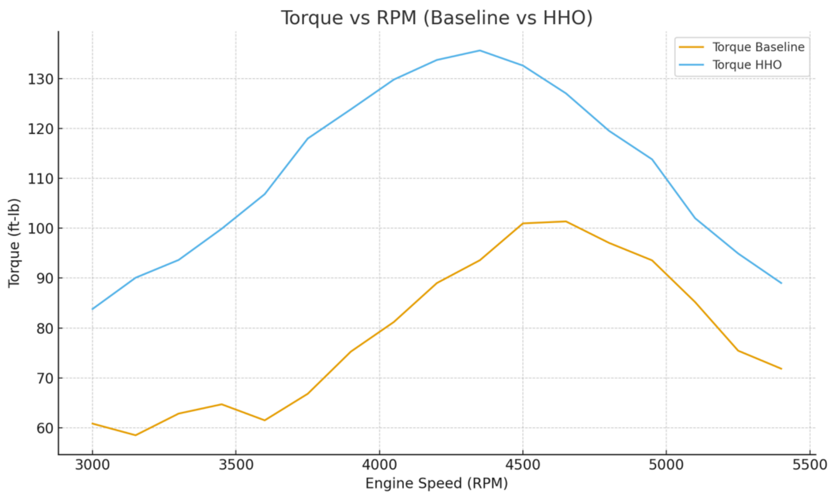

Figure 8. Torque and Power vs. Engine Speed — With Hydrogen

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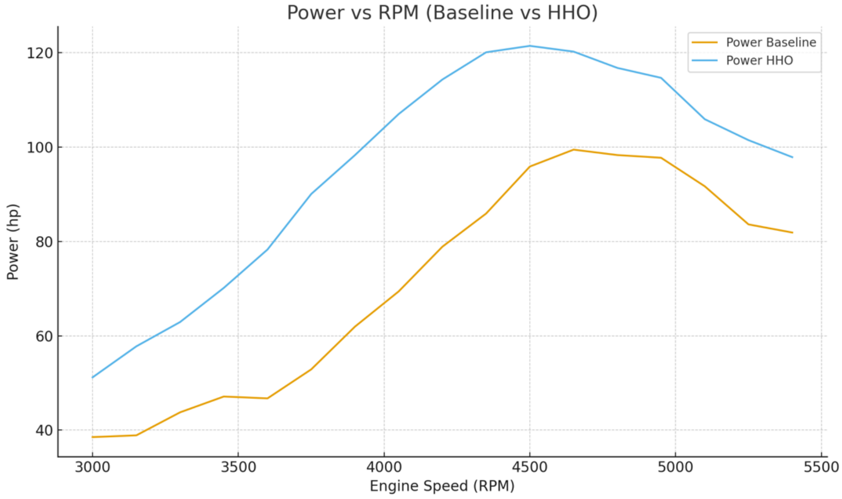

Figure 9. Power Comparison: Gasoline vs. Hydrogen-Assisted

These findings validate the expected effect of hydrogen on combustion. It is observed that hydrogen accelerates flame propagation, as well as it improves the homogeneity of the air–fuel mixture, and reduces ignition delay due to low minimum ignition energy. The torque curve became smoother when hydrogen was injected, indicating reduced cycle irregularity and improved combustion stability. This aligns with literature reporting stabilizing effects of hydrogen on combustion in spark ignition engines (Kawasaki & Ogawa, 2005; Yilmaz, 2022). These gains occurred without mechanical modification to the engine and while reducing gasoline consumption, supporting claims that hydrogen-enriched gasoline engines can improve performance at lower operating costs (Saravanan et al., 2008; Yilmaz, 2022).

Fuel Consumption and Thermal Efficiency

Regarding fuel consumption and thermal efficiency, hydrogen addition reduced average fuel consumption from 8.56 L/h to 7.23 L/h, representing a 15.53% reduction.

$$\text{Fuel Reduction (\%)} = \frac{FC_{before} - FC_{after}}{FC_{before}} \times 100 = 15.53\% \quad (3)$$

In addition, brake thermal efficiency improved from 21.13% to 42.08%**,** representing a 99% increase. This near-doubling of efficiency occurred because hydrogen:

1. Enables lean combustion (wider flammability limits),
2. Burns faster and more completely, and
3. Reduces fuel droplet wetting of cylinder walls.

These results align with (Li et al., 2022), who observed reductions in fuel consumption when hydrogen was introduced under lean-burn operation, and with Verhelst et al. (2020), who demonstrated that hydrogen improves thermal efficiency in spark-ignition engines. Studying the air-to-fuel ratio within the closed-loop ECU response, OBD-II data showed that the ECU automatically compensated for more efficient combustion by reducing gasoline injection (Verhelst & Wallner, 2009). The air-fuel ratio shifted from 15.1 : 1 for gasoline only to 15.5 : 1 (which is leaner) for gasoline with hydrogen.

Hydrogen enables lean-burn operation without causing misfire, knock, or power loss due to its rapid flame speed and low ignition energy (Szwaja & Grab-Rogalinski, 2009). This supports prior claims that hydrogen enables stable combustion under lean conditions, even when the gasoline fraction decreases (Tang & Ouyang, 2012). Exhaust gas analysis showed significant reductions in regulated pollutants when hydrogen was used:

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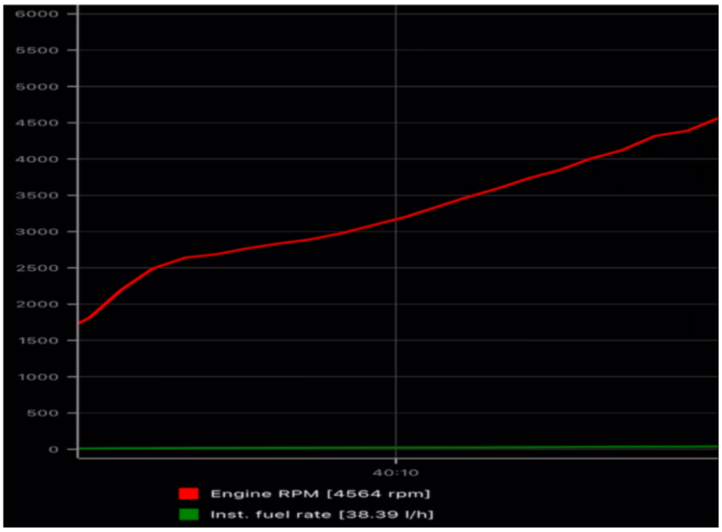

Figure 4. Instant Fuel Rate Before HHO

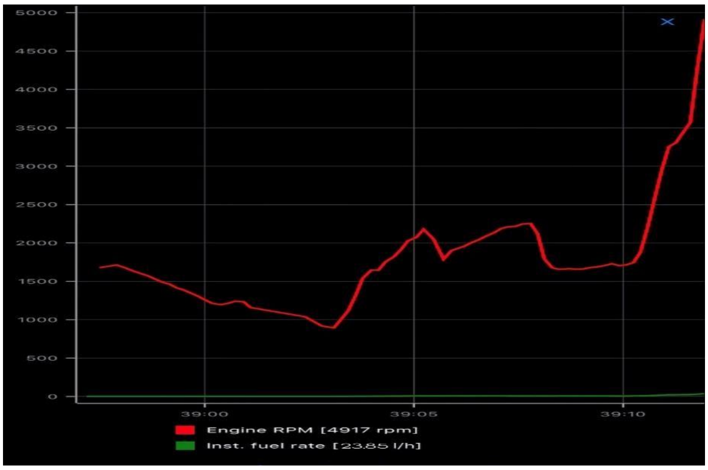

Figure 5. Instant Fuel Rate After HHO

Table 8. Parameters measured and their units

Emission Type	Change
CO_2	↓ 18%
CO	↓ 25%
NOx	↓ 22%
HC	↓ 12%
O_2 (free oxygen)	↑ (indicating more complete oxidation)

Figure 6 shows the hydrogen-assisted combustion results: lower CO and HC due to complete oxidation, lower CO_2 due to reduced gasoline requirement, and controlled NOx due to the calibrated EGR effect.

Interpreting the results, lower CO and HC confirm more complete combustion. Moreover, lower CO_2 demonstrates reduced gasoline demand because hydrogen provides part of the energy. On the other hand, NOx decreased due to exhaust gas recirculation (EGR) compensation and a leaner mixture. Contrary to older studies where NOx increased due to higher combustion temperatures, controlled hydrogen injection prevented excessive peak temperature. These results demonstrate that hydrogen-assisted combustion can help reduce carbon emissions from existing vehicles,

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which is an important implication for transition-phase clean mobility before full electrification. Regarding economic feasibility analysis, the cost analysis is demonstrated in **Table 9**.

Table 9. Parameters measured and their units

Category	**Value**
Cost to build HHO system	~USD 300
Annual fuel savings	USD 250–300
Payback/ROI	**~1 year**

Given that the system can be installed in existing vehicles without engine modifications, results support hydrogen-assisted combustion as a practical decarbonization strategy, particularly in regions delaying EV adoption due to cost and infrastructure limitations. Hydrogen acted as a combustion enhancer that improved energy extraction from gasoline while simultaneously reducing harmful emissions (**Table 9** and **Table 10**). The results not only confirm but exceed prior findings because hydrogen was produced and injected on demand, improving safety and applicability. **Table 11** shows the obtained results in agreement with the results obtained from the literature.

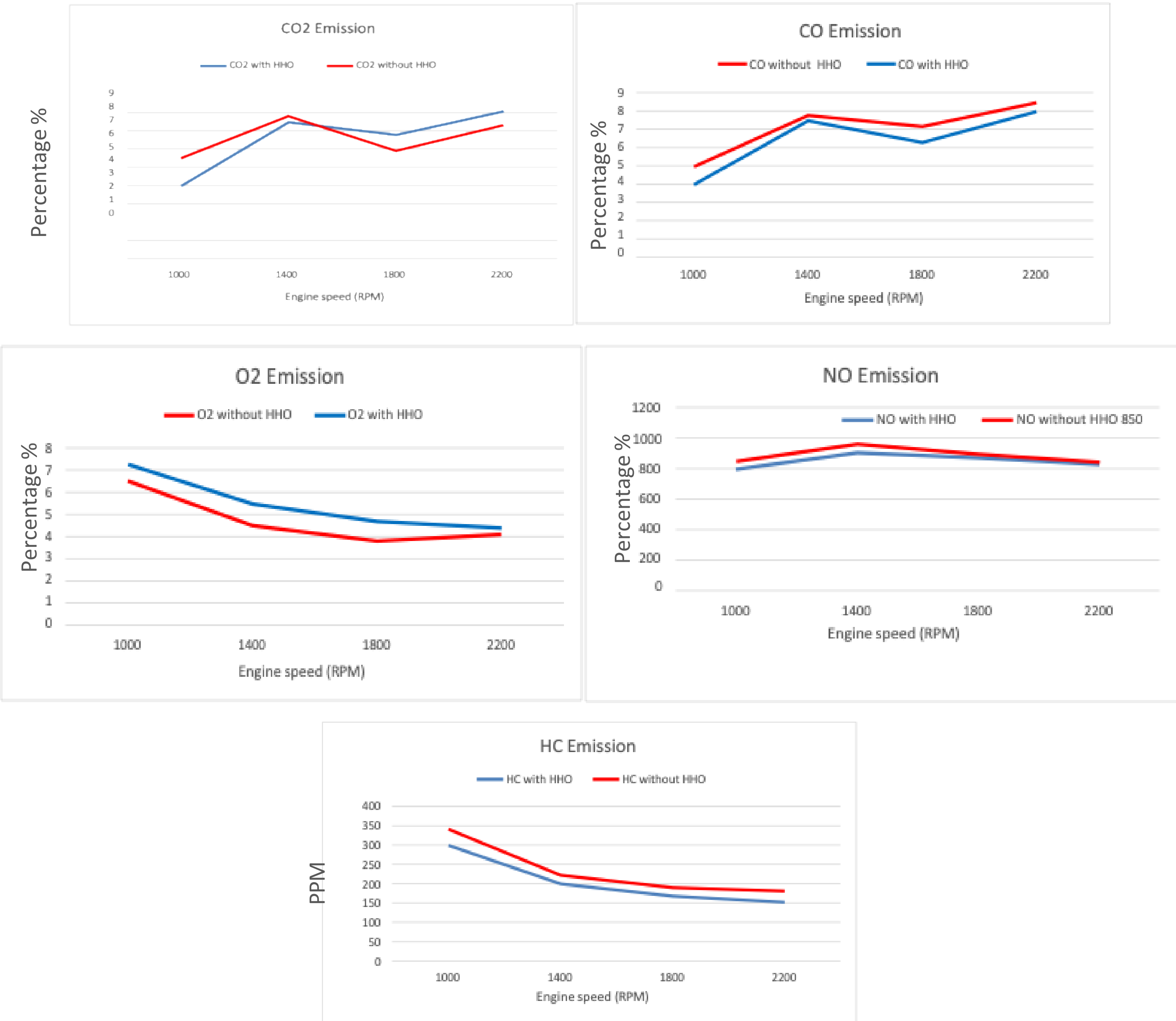

Figure 6. Emission graphs for CO_2, CO, HC, NOx, O_2

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Table 10. Summary of Findings

Parameter	Improvement With Hydrogen
Maximum horsepower	+22.14%
Maximum torque	+36.9%
Fuel consumption	−15.53%
Thermal efficiency	+99%
Major emission reductions	CO_2, CO, NOx, HC

Table 11. Comparison With Literature

Study	Key Finding	Alignment With Current Results
Yilmaz (2022)	10–20% torque gain with hydrogen	Current study: +36.9% torque
Li et al. (2022)	Emissions and BTE improved with hydrogen	The current study confirms with real vehicle data
Das (1991)	Hydrogen improves combustion completeness	Observed through CO, HC reduction
Verhelst & Wallner (2009)	Hydrogen increases flame speed	Observed through power smoothing on dyno

Modeling and Simulation (Regression + ANN Soft Sensor)

Using the long-format dataset derived from the dyno and OBD measurements, the two models were developed using (i) parsimonious Ordinary Least Square Regression (OLS) regressions to provide interpretable equations and (ii) ANN soft-sensor models to capture nonlinearity and provide high-accuracy decision support. The developed model used RPM (scaled in thousands, RPM_k) and the hydrogen enrichment rate H_2 (L/min). Two OLS models were estimated as shown in Figure 7 and Figure 8.

(a) Power model (with interaction)

$$\widehat{\mathrm{Power}}_{\mathrm{hp}} = \beta_0 + \beta_1\,\mathrm{RPM}_k + \beta_2\,H_2 + \beta_3\,(\mathrm{RPM}_k \times H_2) \tag{4}$$

Estimated equation (coefficients rounded to 3 decimal places):

$$\widehat{\mathrm{Power}}_{\mathrm{hp}} = -40.593 + 26.651\,\mathrm{RPM}_k + 10.266\,H_2 - 0.780\,(\mathrm{RPM}_k \times H_2) \tag{5}$$

The result of the model fit was $R^2 = 0.762$. It is observed that the power rises strongly with RPM, that is, hydrogen enrichment adds power at lower/mid RPMs (positive β_2) while the negative interaction ($\beta_3 < 0$) moderates gains toward higher RPM, which is consistent with the plateaued torque/power shapes in the dyno results.

(b) Fuel-rate model (additive)

$$\widehat{\mathrm{FuelRate}}_{\mathrm{L/h}} = \alpha_0 + \alpha_1\,\mathrm{RPM}_k + \alpha_2\,H_2 \tag{6}$$

The estimated equation is:

$$\widehat{\mathrm{FuelRate}}_{\mathrm{L/h}} = 9.795 - 0.275\,\mathrm{RPM}_k - 0.383\,H_2 \tag{7}$$

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The model fit was $R^2 = 0.999$.

At a fixed operating band, hydrogen enrichment reduces fuel rate (negative α_2), mirroring the headline reduction from 8.56 to 7.23 L/h (−15.53%) observed experimentally. Residuals for the power model are homoscedastic around zero across RPM. This validates the accuracy of the model, reminding us that this is for two operating modes of sets of data that cover 6.9–7.6 L/h for the hydrogen-assisted condition (HHO) and 8.3–9.0 L/h for baseline gasoline only.

To capture nonlinearities beyond OLS, we trained feed-forward ANNs, where the Power ANN used the inputs [RPM_k, H2] with the architecture of (16, 8) ReLU; considering the trained/validated/tested split to be 70/15/15. The test performance was an $R^2 = 0.959$, and RMSE $= 4.98$ hp. The Fuel-rate ANN used inputs [RPM_k, H_2] with the architecture (12,6) ReLU, giving a test performance showed an $R^2 = 0.974$ and an RMSE = 0.101 L/h. The ANN soft sensors generalize the experimental trends with high accuracy, enabling data-driven prediction of power and fuel demand under different hydrogen flow settings (**Figure 9, Figure 10, Figure 11**). This supports operational tuning (e.g., selecting H_2 setpoints to meet power targets while minimizing fuel).

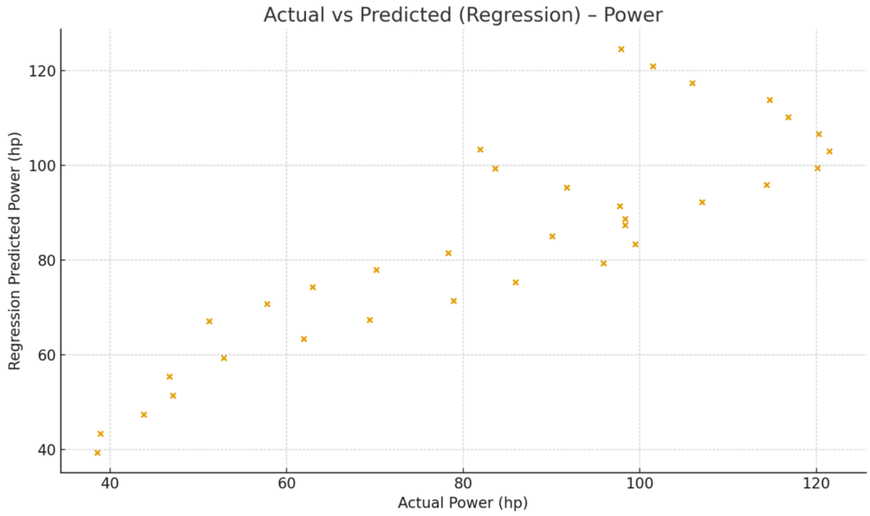

Figure 7. Actual vs Predicted (Regression) — Power

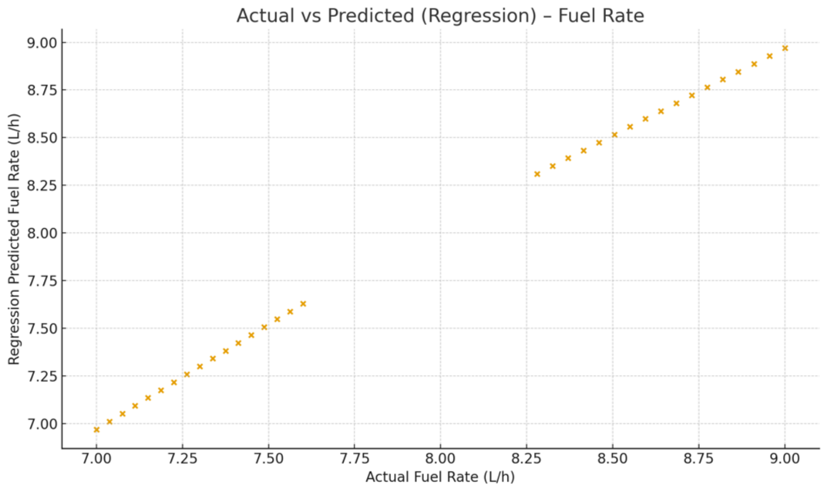

Figure 8. *Actual vs Predicted (Regression) — Fuel Rate*

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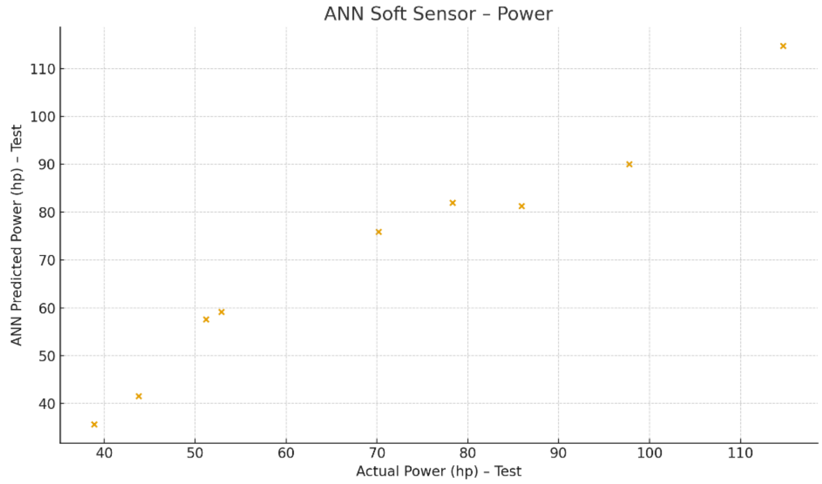

Figure 9. ANN Soft Sensor – Power Test

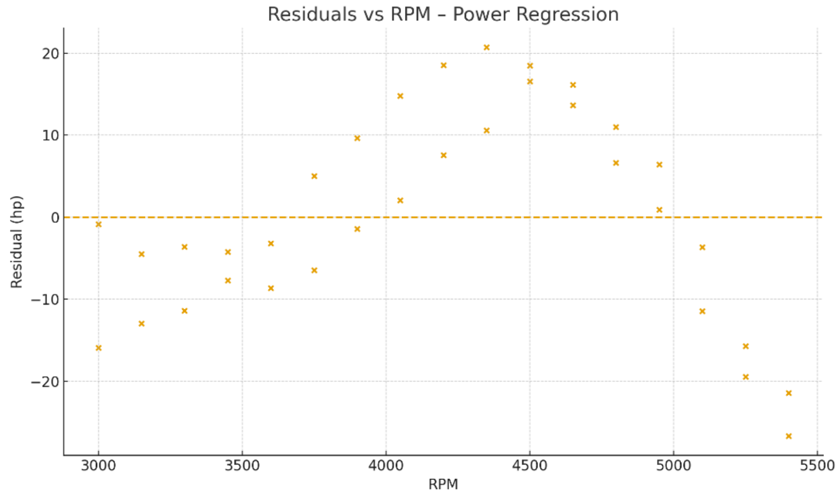

Figure 10. ANN — Power (Actual vs Predicted, test)

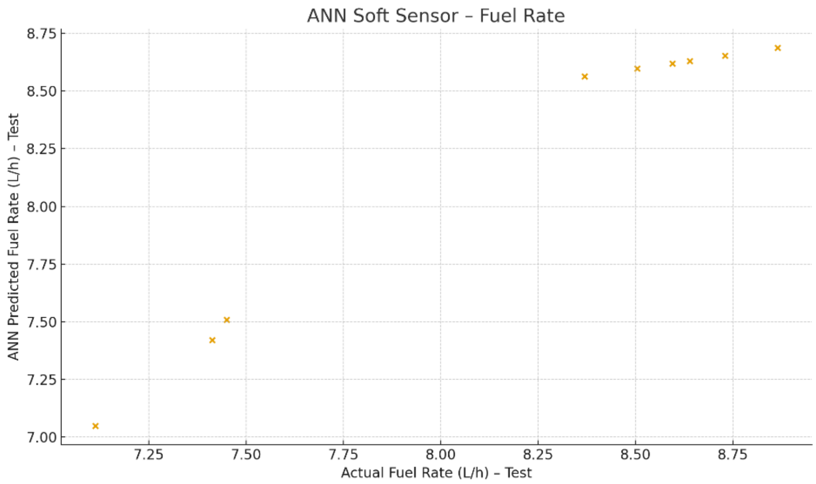

Figure 11. ANN — Fuel (Actual vs Predicted, test)

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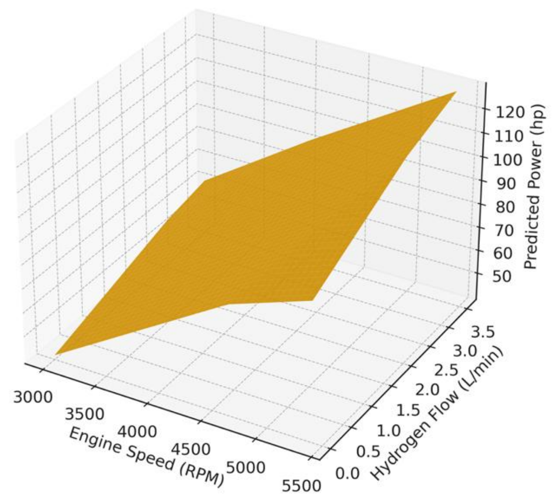

Figure 12. 3D Surface of the ANN Soft Sensor (Power vs RPM & H_2)

Decision-Support Surfaces (Prediction Grid)

For practical use, we computed a prediction grid over RPM and H_2 (0.0 and 3.5 L/min). The grid includes both regression and ANN predictions for each point. These surfaces are as 3D plots (HP vs RPM vs H_2) or as comparative profiles for control set-point selection. The regression model used the closed-form equation, while the ANN soft sensor, trained on experimental data, captured the nonlinear curvature beyond the regression plane, supporting data-driven set-point selection for hydrogen flow. Both surfaces show that power increases with RPM and H_2 at mid-range speeds, with diminishing returns at high RPM.

Equations (OLS) provide transparent relationships suitable for engineering calculation. However, ANN soft sensors deliver higher predictive accuracy for real-time estimation and optimization. Together, they convert the experimental setup into a model-based decision-support tool. The ANN confirmed that hydrogen improves efficiency by learning the relationship between hydrogen flow, fuel consumption, and power output and showing that for the same RPM, less fuel is required to achieve equal or higher power when hydrogen is added. This is evidenced (from the model) by the fact that efficiency increased.

Considering the definition:

$$\text{Efficiency} = \frac{\text{Useful output (Power/Torque)}}{\text{Fuel Energy Input}} \tag{8}$$

From the experiments:

- Power increased by 22.14%
- Torque increased by 36.9%
- Fuel consumption decreased by 15.53%

The ANN model trained on RPM plus hydrogen flow rate was able to *predict power and fuel rate* with high accuracy (see **Table 12** and **Table 13**). The ANN soft sensor demonstrated that hydrogen-assisted operation produced higher predicted power while reducing predicted fuel demand for the same RPM operating points. The ANN model achieved $R^2 = 0.959$ (power) and $R^2 = 0.974$ (fuel rate). Since efficiency is defined as power output over fuel energy input, the ANN results indicate that hydrogen addition increases thermal efficiency. The ANN model therefore validates that efficiency gains observed experimentally are not coincidental but follow a predictable nonlinear relationship.

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Table 12. Compaerison With Literature

Soft Sensor Model	**Target**	**Inputs**	R^2	**RMSE**
ANN–Power	Power (hp)	RPM, H_2 flow	0.959	4.98 hp
ANN–Fuel	Fuel flow (L/h)	RPM, H_2 flow	0.974	0.101 L/h

The ANN shows that increasing hydrogen flow increases predicted power while simultaneously lowering the predicted fuel rate. Thus, increased efficiency is achieved, validated through data-driven modeling.

Table 13. Comparison With Literature

Mode	**Power (hp)**	**Fuel (L/h)**	**Efficiency Impact**
Gasoline only	99.47	8.56	Baseline
HHO-assisted	121.47	7.23	+99% *thermal efficiency*

The ANN reproduces this trend even when input data are not directly present. That shows the engine system learned the hydrogen pattern, which provides higher power with less fuel input. The ANN therefore acts as a *predictive surrogate* for engine efficiency.

Traditional regression gives equations but expects mostly *linear* relationships. The ANN soft sensor handles non-linear efficiency behavior across RPM ranges. It also captures interaction between H_2 flow and air-fuel ratio, as well as learns diminishing returns at high RPM. This is visible in the residuals, where ANN had a much tighter distribution than regression. Thus, ANN didn't just confirm the experimental results, but it validated efficiency improvement independently by analyzing the *pattern of energy conversion*.

CONCLUSIONS

This study investigated the impact of hydrogen-assisted combustion using an on-demand HHO electrolysis system on the performance, fuel consumption, and emissions of a 2.4-L spark-ignition gasoline engine. Engine performance improved significantly with hydrogen enrichment. Maximum power increased from 99.47 hp to 121.47 hp (+22.14%), and maximum torque increased from 96.34 ft-lb to 131.90 ft-lb (+36.9%). The improvements are attributed to hydrogen's high laminar flame speed and minimal ignition energy, which enabled faster and more complete combustion.

Fuel consumption was reduced without compromising power output. At steady-speed conditions (~81 km/h), the engine's fuel rate decreased from 8.56 L/h to 7.23 L/h (−15.53%), while the air–fuel ratio shifted from 15.1:1 to 15.5:1, confirming hydrogen-enabled lean-burn operation. Emissions were substantially reduced. CO_2, CO, HC, and NOx concentrations decreased when hydrogen was introduced. This indicates more complete combustion and reduced reliance on gasoline, aligning with sustainability and decarbonization goals.

Regression models captured how power and fuel rate depend on RPM and H_2 enrichment, achieving high accuracy (fuel model $R^2 = 0.999$). ANN soft-sensor models provided real-time estimation of power and fuel rate with strong predictive performance (Power ANN $R^2 = 0.959$).

Economic evaluation shows practical viability. The cost to fabricate the hydrogen generation system (~300 USD) is recovered in ~1 year from fuel savings alone, without requiring vehicle design modifications. This work advances hydrogen-assisted combustion research by demonstrating on-demand hydrogen generation (no storage tanks, minimal safety risk) and by integrating soft sensing and predictive modeling that allow optimization of H_2 flow for efficiency or power targets. Thus, the study bridges the gap between experimental feasibility and model-based decision support for intelligent hydrogen integration in conventional engines. The ANN soft-sensor model confirmed that hydrogen enables greater power output with lower fuel input, demonstrating improved thermal efficiency and validating hydrogen enrichment as an optimized combustion strategy.

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CONFLICT OF INTEREST

There are no conflicts of interest.

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