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Hydrogen-Enriched Compressed Natural Gas Transition for Low-Emission Operation in Stationary Genset Engines

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Abstract: The degradation of ambient air quality in urban regions of India has been exacerbated by the expansion of automobile fleets and stationary engines. In response, the Central Pollution Control Board (CPCB), under directives from the Ministry of Environment, Forest, and Climate Change (MoEF&CC) and the National Green Tribunal (NGT), has implemented stricter emission norms, including CPCB IV+ standards for power generators. Concurrently, the escalating costs of diesel gensets, driven by the integration of advanced air-fuel systems and emissions control technologies, have necessitated the exploration of alternative fuels. Hydrogen-enriched compressed natural gas (HCNG), a blend of hydrogen and natural gas, has emerged as a promising solution for achieving low emissions while maintaining power performance. This study evaluates the application of an 18% HCNG blend in a genset engine initially compliant with CPCB II standards, achieving compliance with CPCB IV+ emission norms without requiring hardware modifications. Key calibration parameters, including injection timing, ignition timing, injection duration, and desired lambda, were optimized to ensure enhanced performance and emissions control. The in-cylinder combustion characteristics, including combustion pressure, temperature, rate of heat release (RoHR), and brake mean effective pressure (BMEP), were thoroughly analysed for both Piped Natural Gas (PNG) and the HCNG blend. The results indicate that the HCNG blend significantly reduces emissions, with reductions of 66% in carbon monoxide (CO) and 74% in methane (CH_4) compared to PNG. These findings underscore the potential of HCNG to serve as a transitional fuel, bridging the gap towards the adoption of pure hydrogen technologies. This study demonstrates that HCNG can achieve substantial reductions in regulated emissions while supporting cleaner and more sustainable energy systems, positioning it as a viable alternative for stationary power generation applications.

Keywords: Hydrogen; Hydrogen-enriched compressed natural gas (HCNG); Stationary engines; Emissions reduction; Combustion analysis; Environmental sustainability

1 Introduction

The contemporary challenge of climate change is a complex web of interrelated issues. The rising local temperature is one of the main issues, as it has profound effects on ecosystems, human health, and agricultural output [1]. The disturbance of atmospheric and oceanic currents brought about by rising temperatures affects weather patterns and increases the frequency of extreme events like heat waves, flash floods, and cloud bursting [2]. Globally, these alterations represent serious adverse effects to ecosystems and communities that are already at risk. The off-road sector is a rising contributor to India’s greenhouse gas emissions. The global stationary genset market size was $23.04 billion in 2022, and the market is expected to grow at a CAGR of 6.38% by 2029 [3]. Moreover, the country’s electricity demand is increasing rapidly due to the increasing population and carbonization. The demand for energy is placing strain on the current power grid systems, which results in an imbalance in supply and affects customers through load shedding and uneven voltage. During the projected period, these factors are anticipated to propel the gas genset market in India. The genset share for the Indian market was studied, and it was found that the major sector is operating on the diesel genset. The market share for the genset power rating is shown in Figure 1. The current scenario in India (2024), based on power rating, the market is classified into 5 kVA–75 kVA, 76 kVA–375 kVA, 376 kVA–750 kVA, and above 750 kVA. In terms of volume, the category of 5 kVA–75 kVA gensets is estimated to hold the largest share in the Indian diesel and PNG genset market in 2022 [4]. These gensets are employed in high volumes at residential and small commercial installations, construction projects, and telecom towers, in order to meet prime and auxiliary power requirements. The Indian gas genset market is moderately fragmented. Apart from the diesel genset, Kirloskar Oil Engines Limited, Cummins Inc, Caterpillar Inc, General Electric Company, Kohler Co., AKSA Power Generation, Cooper Corporation, Yanmar Co. ltd, Verder Ltd are the key players in gas genset manufacturing in India. The below figure represents the Indian diesel genset market growth for the last decade.

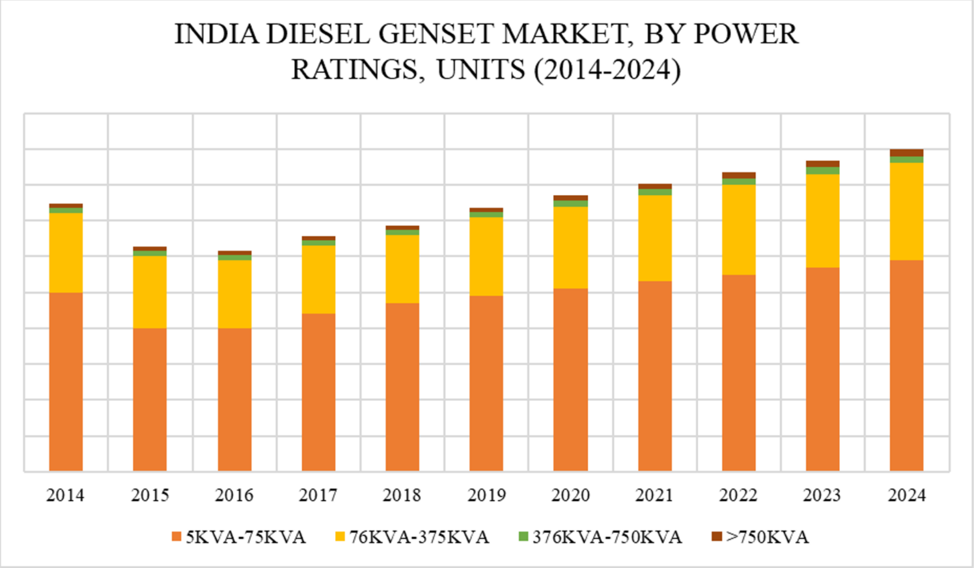

Figure 1. India’s genset market by power rating, units (2014-2024) [5]

In the power-generating sector, being green is the newest entity, and gensets are no exception. In the National Capital Regions (NCR), the NGT issued an order to replace the diesel generator (DG) set that has been in operation for over 15 years with cleaner fuel. The NGT has instructed the CPCB, which is part of the MoEF&CC, to create clean fuel and modify the emission guidelines for stationary engines. India moved from CPCB II to CPCB IV+ emission norms for gensets up to 800kW from July 2023. The announcement of CPCB IV+ emission limits in November 2022 by the Indian government is indicative of the government’s commitment to combating air pollution, and this regulatory move is expected to have a significant influence on the genset industry as a whole. This shift is a calculated step that will steer the industry in the direction of a more sustainable path rather than just changing the regulations.

It is unseemly to assume that the entire transport sector can be electrified soon for a variety of techno-economic factors. Estimates show that the contribution of liquid and gaseous fuels in stimulating India’s transport sector will remain higher than 50% [6]. This indicates that researchers have to find a solution to achieve a net zero scenario. As an alternative to conventional fuel, green hydrogen can play a pivotal role in the net zero goal. The National Green Hydrogen Mission gives an outline of the ambitions of India to become a green hydrogen hub [7]. The availability of green hydrogen is inadequate. As a result, there is still a shortage of hydrogen. To address this issue, the idea of doping hydrogen into natural gas has drawn interest. This will help to ensure that energy is accessible and egalitarian as we move towards a hydrogen-based economy. The doping of hydrogen has shown promising results in improving combustion and mitigating carbon dioxide (CO_2) from tailpipe emissions [8]. The HCNG blend delivers notable improvement in engine efficiency as compared to natural gas. Globally, hydrogen is being blended (15-30% v/v) with natural gas and then compressed to dispense into vehicles. Countries like the United States, Brazil, Canada, and South Korea have all conducted trials and found that they get a reduction in emissions from public transport buses using HCNG.

HCNG technology is an emerging and transformative solution for cleaner energy, especially for retrofitting existing Piped Natural Gas (PNG) genset engines. HCNG is a blend of hydrogen and natural gas, typically consisting of 10%–30% hydrogen by volume. This combination leverages the high combustion efficiency of hydrogen while utilizing the existing infrastructure and availability of natural gas. The potential of HCNG to improve engine performance, reduce emissions, and contribute to the transition towards sustainable energy systems has been extensively examined in the literature.

One of the primary advantages of HCNG is its ability to improve the combustion efficiency of PNG genset engines. Hydrogen's high flame speed and low ignition energy facilitate faster and more complete combustion, which results in reduced unburnt hydrocarbons and higher thermal efficiency. Mehra et al. [9] emphasized in their study that HCNG engines achieve stable operation even at leaner air-fuel mixtures, thereby lowering fuel consumption while maintaining consistent performance. Kang et al. [10] further highlighted that HCNG engines demonstrate better combustion stability under variable operational conditions, a critical factor for genset engines operating under fluctuating loads. Additionally, minimal modifications, such as recalibrating fuel injection systems, are required to adapt PNG genset engines to HCNG. Lounici et al. [11] confirmed that HCNG is compatible with existing infrastructure, making it a cost-effective and scalable solution. Another key advantage of HCNG is its potential to significantly reduce emissions, including greenhouse gases (GHG) and air pollutants. Hydrogen's zero-carbon combustion directly reduces (CO_2) emissions, with Mehra et al. reporting a decrease of up to 20% when a 20% hydrogen blend is used. Lower unburnt hydrocarbons, particulate matter, and CO emissions further contribute to HCNG's environmental benefits, as noted by Kang et al. [10]. However, a challenge associated with HCNG is the potential increase in nitrogen oxides (NOx) due to higher combustion temperatures. Researchers suggest solutions such as optimizing hydrogen blending ratios and incorporating exhaust gas recirculation (EGR) systems to address this issue.

The environmental benefits of HCNG are further amplified when the hydrogen component is derived from renewable sources. If green hydrogen, produced using renewable energy, is utilized, the overall lifecycle emissions of HCNG are drastically reduced, enhancing its sustainability credentials. Gupta et al. [12] argue that HCNG serves as a transitional technology, leveraging existing natural gas infrastructure while paving the way for a hydrogen-driven energy economy. This dual advantage of immediate environmental impact and long-term scalability positions HCNG as a critical bridge between fossil fuels and future clean energy systems.

Hora and Agarwal [13] have selected a single-cylinder constant-speed research engine to evaluate various HCNG blends, where he has reported that brake thermal efficiency (BTE) increases with hydrogen percentage increase in HCNG due to superior combustion stability. The BTE was recorded as 28%, 28.6%, 29.3%, and 29.7%, respectively, for CNG, 10HCNG, 20HCNG, and 30HCNG at maximum BMEP. Hydrogen addition in CNG also increases the lean limit for CNG operation. Further addition of hydrogen in CNG increased the burning rate, resulting in a shorter combustion duration. A lesser BSFC was obtained due to an increase in HCNG calorific value. HCNG delivered slightly higher peak firing pressure with earlier SOC [13]. RoHR was higher for HCNG mixtures due to higher flame speed because of hydrogen addition. Thermal NOx formation was observed due to relatively higher peak firing temperatures owing to the presence of hydrogen. The same study also highlights the effect on performance, combustion, and emission characteristics with varying compression ratios under identical conditions. It was reported that the in-cylinder pressure, temperature, and RoHR increase further with a rise in compression ratio. NOx emissions degrade with an increase in compression ratios [14].

Sagar and Agarwal [15] investigated the knocking pattern for HCNG blends. Hydrogen enrichment in CNG increased the flame propagation speed and reduced the quenching distance. The reduced quenching distance and the presence of OH and O radicals in the air-fuel mixture developed a tendency to pre-ignite. Hence, higher HCNG blends have more severe knocking characteristics because of this hydrogen feature. As a result, knocking got worse at higher BMEPs due to increased fuel injection volume and hydrogen presence.

Park et al. [16] studied the full load performance and emission outcomes of HCNG engines with valve overlap changes and concluded that HCNG possesses a stable lean combustion characteristic. In his study, various strategies of valve overlapping were employed to reduce CH_4 emission control. De Simio et al. [17] have reported a study on a 15% and 25% HCNG blend in a heavy-duty spark-ignited engine, where, with the help of decreasing spark advance set values, the combustion barycenter and the NOx emission magnitude are made similar to CNG. Barbu et al. [18] in his simulation study has found that HCNG, being a gaseous fuel, has better homogeneity compared to liquid fuel, which helps in the significant reduction of HC and CO emissions. Singh et al. [19] in their study have reported a significant reduction of unregulated emissions, viz. formaldehyde, acetylene, formic acid, benzene, ethane, and propane, and specific fuel consumption with HCNG is better than CNG. When material compatibility is a concern, as hydrogen has a metal embrittlement tendency, an 18-30% v/v HCNG blend was tested on metallic and non-metallic fuel components by Dekate et al. [20]. Outcomes of this study state that there was no adverse effect of HCNG on the metallic component, and the non-metallic component has a closer band with CNG. In this 1D simulation study, Kavathekar et al. used GT-Suite to model a CNG engine and compare its performance with a 15% HCNG blend. In this study, the effect of varying fuel-air equivalence ratios on optimum spark timing, peak-cylinder pressure, and in-cylinder temperature was validated through simulation. The simulation predicted results show encouraging improvements in the brake-specific fuel consumption (BSFC) with a definite improvement in brake power with a 15% HCNG blend [21].

Wang et al. [22] studied the various fractions of HCNG blend in a direct injection engine, where a constant fuel injection pressure of 80 bar is maintained. In his study, the volumetric heating value decreased by 24% when the hydrogen volumetric fraction in fuel blends reached up to 37%. Since hydrogen has a lower volumetric heating value than natural gas, the volumetric heating value of the blend drops as the hydrogen proportion in the fuel blends increases. Therefore, in the instance of HCNG blends, more fuel injection time is required to maintain the same level of heat release in direct injection technology. In another study, Huang et al. [23] reported the combustion behavior of the HCNG fuel with direct injection. Flame development duration decreases with advancing the ignition timings. To create high mixture stratification in the combustion chamber and a relatively rich mixture near the spark plug, advancing the ignition timing will shorten the time interval between the end of fuel injection and ignition timing. This will make the mixture easier to ignite, which will shorten the time it takes for a flame to ignite and develop. The addition of hydrogen can encourage flame kernel formation and flame propagation at the early stages of mixture combustion, as evidenced by the fact that the flame development period decreases with an increase in hydrogen proportion for a given ignition timing [23].

Among the research papers on HCNG study [24–28], most of the authors have studied the performance and emissions parameter outcomes for HCNG from 5-50% v/v, some did the combustion analysis and showed the effect of hydrogen on combustion. All this research work was done using either port fuel injection or direct injection technology. Few studies presented on venturi-type mixers used for HCNG fuel mixing on power-generating engines [29, 30]. And despite the advantages of HCNG, it is worth noting that the increased risk of engine knocking with higher concentrations of hydrogen in the blend requires careful tuning of the air/fuel ratios and their calibration. Additionally, the cost-effectiveness of scaling HCNG technology depends on advancements in hydrogen production and distribution. This paper addresses these technical barriers and thus focuses on the usage of venturi-type mixers for HCNG fuel supply for genset engines and also the economic barriers while exploring HCNG's long-term impacts on engine durability.

The enactment of HCNG as a fuel in Genset engines has not been explored, and the development is subject to extensive research, demonstrating significant benefits in emissions reduction and performance optimization. In a comprehensive review by Ajmeri et al., it is highlighted that blending HCNG with diesel (Dual Fuel Mode) can lead to a reduction in CO, total hydrocarbons (THC), and CH_4 emissions by 39%, 25%, and 25%, respectively, while maintaining similar power outputs compared to pure CNG operations conducted in an optical single-cylinder research engine [31, 32]. Further research by Yadav et al. [33] focused on a constant-speed spark-ignition engine fueled with HCNG. The study demonstrated that HCNG usage led to improved thermal efficiency and a significant reduction in CO and THC emissions. These results underscore HCNG's potential to enhance engine performance while mitigating environmental impact. Additionally, an experimental analysis by Subramanian et. al. compared the exergy efficiency of a multi-cylinder spark-ignition engine fueled with CNG, HCNG, and hydrogen [28]. The study concluded that HCNG offers a balanced performance with better exergy efficiency than CNG, highlighting its suitability as a transitional fuel towards hydrogen. Theoretical analyses suggest that HCNG's higher flame speed enhances combustion stability, which is crucial for achieving lower emissions in compression ignition engines [34]. Overall, the literature suggests that HCNG fuel is not used for the development of Power Generating set, however the stringent emission norms and transition towards net zero by 2070 will position HCNG as a promising fuel for future genset applications. The application of HCNG in the automotive sector is extensive; however, its use in power generator set (genset) applications is relatively novel, with only a limited amount of academic literature currently available on this topic. This highlights the originality of our work. In contrast, PNG is commonly utilized in power generation, and therefore, the relevant literature on PNG is referenced in the introduction section to serve as a baseline for comparison with our current study.

This study further simulates the performance and emission outcomes of the genset engine fueled with 18% HCNG. Here a 62.5 kVA rating CPCB II emissions-compliant in-use genset with PNG was selected to optimize for the HCNG. Based on the gap analysis, the engine was calibrated to run on 18% HCNG and finally certified for CPCB IV+ emission norms. The literature study and the market share data gave us a clear image that the 62.5 kVA rating engine has the higher market share and is mostly fueled by diesel and PNG based on its supply and availability. The motivation behind this study is to implement HCNG fuel for genset engines and to decarbonize the stationary sector. The objectives of this study are listed below.

- Achieve a specific goal for conversion of in-use PNG genset into HCNG.
- Selection of in-use 62.5 kVA PNG genset engine.
- DFMEA of the fuel system and component.
- Sourcing of 18% HCNG fuel from INOX Airproducts Pvt Ltd. Fuel specification validation as per IS 17314:2019.
- Baseline engine performance and emission trial with PNG and HCNG for gap analysis.
- In-cylinder combustion data analysis.
- Engine tuning with HCNG fuel to meet emissions and performance.
- Engine endurance test for 100 hours with HCNG.
- Consistency trial with HCNG fuel to validate the performance and emissions.
- Considering directives of CAQM in New Delhi, India the introduction of the HCNG Power Generating Set will

be more useful for converting in-use CPCB II genset to CPCB IV+ without investing much in after-treatment devices.

The main novelty of the developmental work is using HCNG injection through a gas mixer in the intake system of the genset engine at atmospheric pressure. Therefore, there will not be any modification in the fuel injection system, and the USP will be retained. In a nutshell, the integration of HCNG in power generators and constant-speed engines presents a promising avenue for enhancing performance and reducing emissions. The collective findings from these studies advocate for the adoption of HCNG as a feasible alternative fuel, offering environmental benefits and operational efficiency in power generation applications.

2 Experimentation

According to the project objectives, a methodology for the developmental activity was finalized. The base PNG genset engine was mounted on the test rig and coupled with a steady-state eddy current dynamometer with all the necessary data acquisition systems. Provision for in-cylinder pressure measurement was made. A piezoelectric pressure transducer was used to measure the in-cylinder pressure connected with a High-Speed Data Acquisition (HSDA) system, which acquires the combustion pressure signal for each engine crank angle in degrees. Pressure-crank angle data was logged for 300 consecutive combustion cycles to monitor the cycle-to-cycle variation. The selection of 300 combustion cycles was made to ensure minimal variation from cycle to cycle. Although it's possible to acquire data from a minimum of 50 combustion cycles, this approach tends to yield a high Coefficient of Variation (CoV). On the other hand, while selecting a larger dataset of 500 cycles would provide more data, it would also result in a significantly larger volume for processing. Therefore, the decision was made to work with 300 cycles of data. Raw emission gas analyzers were used to measure the harmful emissions, and data were logged at 10 Hz. In accordance with part 4 of ISO 8178, it is essential to use a raw emission gas analyzer that operates with a data logging frequency of 10Hz. This specific analyzer is crucial for accurately measuring the emissions produced by a generator engine. These measurements are necessary to ensure compliance with the emission standards set forth by the CPCB. By capturing data at this frequency, we can obtain precise readings essential for calculating emissions effectively. A provision of the lambda sensor (oxygen sensor) was made for continuous lambda monitoring and to map the desired lambda for efficient catalytic converter conversion. Other than the above, the pressure sensors (gauge and differential type) and temperature sensors (RTD and K-type thermocouple) in the engine intake, exhaust, oil and coolant system were connected. Below are the listed equipment used during the developmental trials; their measurement range and accuracy are shown in the subsequent Tables 1-3.

Table 1. Make and model of equipment used [35]

Equipment	Make
Engine Steady State Dynamometer	SAJ, AG-150
Test Cell PLC Automation	IASYS, ORBIT-E
Conditioned Air Handling Unit	KS_ENG_IACU3000
Air Flow Meter	ABB Sensyflow, SFI-02
Fuel (Gaseous) Flow meter	Krohne-Marshall
Emissions Analyser	AVL AMA i60-01
Opacity Meter	AVL 439
Smoke Meter	AVL 415
PM Analyser	AVL, SPC-472-05
Blow by Meter	AVL 442
Combustion Data Measurement System	AVL Indi Micro

Table 2. Emission analyzer measuring range and accuracy [35]

Emission Type	Measurement Range	Accuracy
CO (Low)	$50 - 5000$ppm	$\pm 1\%$
CO (High)	$1 - 12\%$vol	$\pm 1\%$
THC	$50 - 30000$ppmC	$\pm 1\%$
CH_4	$50 - 20000$ppmC	$\pm 1\%$
NO, NO_2, NOx	10-5000 ppm	$\pm 1\%$
CO_2	$5 - 20\%$vol	$\pm 1\%$
O_2	$1 - 25\%$vol	$\pm 1\%$
Smoke	$0 - 10$ FSN	$\pm 3\%$

Table 3. Combustion sensor specifications

Measuring Range	$0 - 250\text{bar}$
Sensitivity	$19\text{pC}/\text{bar}$
Linearity	$\pm 0.3\%$
Natural Frequency	160 kHz
Acceleration Sensitivity	$\leq 0.0005\text{bar}/\text{g}$

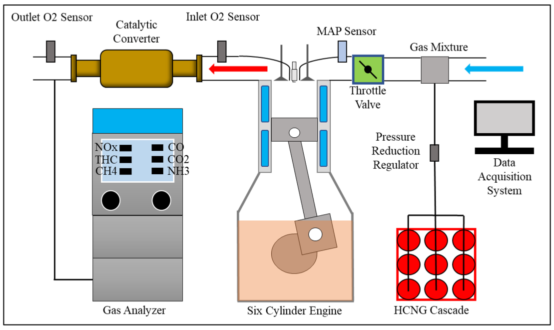

Figure 2. Schematic layout of engine testing setup

Table 4. Genset engine configuration

Engine Parameters	**Specification**
Type	Gas Genset
Engine Rating	62.5 kVA
Rated Power	61 kW
Speed	1500 RPM Constant
No. of Cylinders	06 Nos.
Engine Displacement	6.5 Litres
Aspiration	Natural
Fuel System	Gas Mixer
After-Treatment Device	TWC

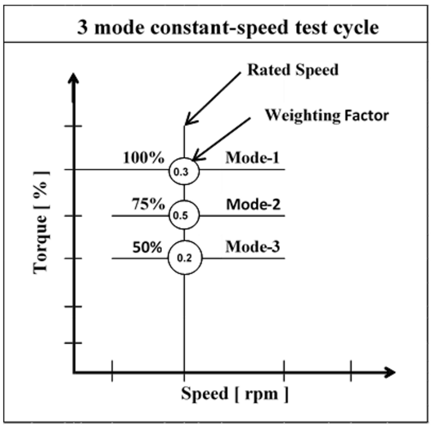

Figure 3. D1 3- Mode Cycle as per ISO 8178

The test cell layout is shown in Figure 2. In this case, the HCNG fuel is stored at 200 bar pressure. In practical scenarios, natural gas generator sets are connected to a piped natural gas supply that delivers gas at a pressure ranging from 5 mbar to 1.2 bar. To simulate this condition in a test lab, a two-stage pressure-reducing system is necessary. A single-stage pressure reduction system (PRS) is inadequate, as it would cause an adiabatic cooling effect when reducing pressure suddenly from 200 bar to atmospheric pressure. This cooling effect can lead to freezing, resulting in a fuel shortage and potentially starving the generator of fuel. A two-stage PRS was mounted in the fuel delivery line to supply the HCNG fuel at atmospheric pressure. As the fuel delivery for the gas genset engine was through the mixer, the inlet pressure was maintained through a zero pressure regulator (ZPR) system, which will maintain a pressure of -5 to 5 mbar.

The specification of the genset engine developed under this project is shown in Table 4.

The emission test cycle followed here is the D1 3-Mode Cycle as per ISO 8178. D1 3-Mode is a constant-speed cycle where the emission is measured in a steady-state condition for three different discrete modes, where the load on the engine is considered as 100%, 75%, and 50%, respectively. The 3-mode cycle is shown in Figure 3.

3 Engine Calibration

Table 5. PNG fuel report as per IS 15958:2023 standard

Parameters	Unit	Observed Values
Wobbe Index	$\mathrm{MJ/m^3}$	49.1
Water Content	$\mathrm{mg/m^3}$	2.36
Methane	% Volume	95.35053
Ethane	% Volume	1.85753
Propane	% Volume	0.84858
I - Butane	% Volume	0.14149
N - Butane	% Volume	0.20414
I - Pentane	% Volume	0.04939
N - Pentane	% Volume	0.04371
Hexane	% Volume	0.06511
Nitrogen	% Volume	0.23889
Carbon dioxide	% Volume	1.20056
Gross Calorific Value	Kcal/$\mathrm{m^3}$	9252.843
Net Calorific Value	Kcal/$\mathrm{m^3}$	8342.264
Specific Gravity	-	0.59321

Table 6. HCNG fuel properties tested as per IS 17314:2019

Parameters	Units	Observed Values
Water content at STP	$\mathrm{mg/m^3}$	< 5
Total Sulphur	ppm (v/v)	< 1
Hydrogen	% Mole	16.675
Oxygen	% Mole	0.186
Nitrogen	% Mole	1.117
Carbon Dioxide	% Mole	0.193
Carbon Monoxide	% Mole	< 0.01
Methane	% Mole	74.711
Ethane	% Mole	5.452
Propane	% Mole	1.201
Isobutane	% Mole	0.205
Butane	% Mole	0.241
Isopentane	% Mole	0.011
Pentane	% Mole	0.008
Cyclopentane	% Mole	< 0.001
2,2-Dimethylbutane	% Mole	< 0.001
2,3-Dimethylbutane + Iso-hexane	% Mole	< 0.001
Hexane + 3- Methylpentane	% Mole	< 0.001
Benzene + Cyclohexane	% Mole	< 0.001
2-Methylhexane	% Mole	< 0.001
3-Methylhexane	% Mole	< 0.001
Heptane	% Mole	< 0.001
Methylcyclohexane	% Mole	< 0.001
Toluene	% Mole	< 0.001
2-Methylpentane	% Mole	< 0.001

In CPCB IV+ norms, the deterioration factor for emissions is applicable. In CPCB II norms, crankcase ventilation kept open to the atmosphere was allowed; however, in CPCB IV+, it has to be closed for engine ratings above 56 kW, which proves to be a challenging part when compared to CPCB II norms. As the gas engine running on PNG selected for this research work is CPCB II compliant, therefore, to analyze the gap, experimental trials for emissions as per CPCB IV+ norms were conducted. The emission test was conducted with an 18% HCNG blend on the genset engine with the same PNG configuration. The NOx and NMHC emissions were found to be higher for 18% HCNG compared to PNG. The reason behind the emission increase is that the engine was not calibrated for HCNG fuel. To optimise the engine for 18% HCNG fuel, the engine tuning parameters, viz. Volumetric efficiency, maximum brake torque, and desired phi, are calibrated. The in-cylinder pressure data were also analysed during the development. During this trial, PNG and 18% HCNG fuels are used. Both the fuels are tested as per BIS standards. The fuel reports are shown in Table 5 and Table 6. After the upgradation of the engine, the performance and emission trial are done on the genset engine with HCNG fuel. An endurance test of 100 hours is also conducted with the HCNG fuel to analyze the effect of HCNG fuel on the fuel systems and engine components. Engine lubrication oil sampling was done at every 50-hour interval and analyzed for any irregularity. An emission consistency trial was also taken with 18% HCNG fuel to see the repeatability.

4 Results and Discussion

Developmental trials were performed to study the combustion, performance, and emissions outcomes of HCNG after the engine tuning. As this was a genset engine, it has a constant speed operation of 1500 rpm. Therefore, as per ISO 8178 test standards, the performance and emission parameters at engine loads of 100%, 75%, and 50% were measured. At engine equivalent BMEP of 7.5, 5.63, and 3.74 bar, the combustion data was recorded, and the results for engine combustion, performance, and emissions were experimentally evaluated, and the results are shown in the subsequent sub-sections. The dynamometer is operated in the RT (Speed-Torque) mode as the engine was a constant speed engine. In RT mode, the dynamometer controls and restricts the speed and load, i.e., brake torque, of the engine, and the throttle was set by the engine ECU to overcome the particular load. For ease of comparison and certain performance parameters determination, the calorific value and energy density for PNG and HCNG are calculated and are shown in Table 7. The energy density of an 18% HCNG blend is found to be lower than that of PNG; this is due to the physical characteristics of hydrogen, which has a density of approximately 0.13 times the density of natural gas.

Table 7. Fuel calorific value and energy density

Fuel	Lower Calorific Value (kJ/kg)	Energy Density $(\mathbf{KJ/m^3})$
CNG	48961.16	35080.10
18% HCNG	50742.63	30709.68

4.1 Combustion Characteristics

The in-cylinder combustion pressure, temperature, and RoHR variation were observed at different BMEP for CNG and 18% HCNG. The comparison of peak pressure at a maximum BMEP of 7.5 bar for CNG and an 18% HCNG blend is shown in Figure 4. The presence of hydrogen in CNG has shown a higher peak pressure as compared to PNG, and the in-cylinder peak pressure is increased by 2.2%. This increase in peak pressure for HCNG fuel is due to the sole property of hydrogen to propagate the flame progress phase. Natural gas is a slow-burning fuel compared to hydrogen, so enrichment of hydrogen in natural gas improves flame propagation. The higher diffusivity of hydrogen also aids in improving the air-fuel mixture and advances the combustion rate. The higher flame speed of 18% HCNG has shortened the combustion duration, and a faster flame kernel is achieved, which led to the earlier start of combustion as compared to PNG.

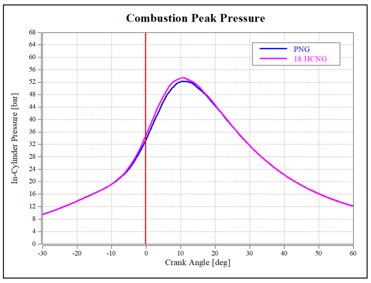

Figure 4. Combustion in-cylinder pressure at max. BMEP

The in-cylinder temperature and the RoHR are also evaluated at the maximum BMEP of the engine for PNG and 18% HCNG fuel, as shown in Figure 5 and Figure 6, respectively.

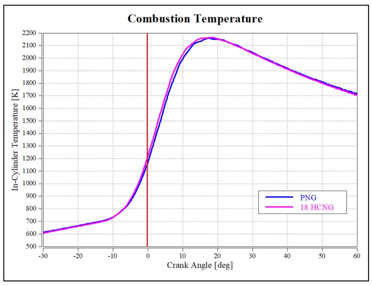

Figure 5. Combustion in-cylinder temperature at max. BMEP

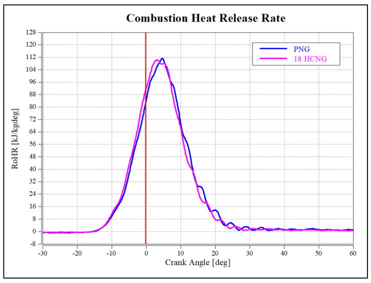

Figure 6. Combustion RoHR at max. BMEP

The in-cylinder combustion temperature for the 18% HCNG blend is observed in a higher magnitude than the PNG till MBF90%. This is due to the hydrogen's higher flame speed, which increases the enthalpy of formation. In the case of PNG, the afterburning took place that is more significant than the HCNG blend, which emits a large fraction of chemical energy at the later stage of the expansion stroke. Thus, PNG shows a higher in-cylinder temperature rate after the MBF90% compared to 18% HCNG. The RoHR curve peak for 18% HCNG is shifted towards TDC as compared to PNG; this is due to the hydrogen's higher flame speed, higher degree of constant volume combustion, and energy content. Generally, for positive ignition engines, there are three combustion stages, viz. flame progress, flame propagation, and afterburning. Typically, the flame progress is the phase over the crank angle where MBF5% has been achieved, the crank angle between the MBF5% to MBF90% is the flame propagation and the crank angle over MBF90% is after burning. Controlling the flame propagation phase in the case of the positive ignition engine is very vital and decides the engine's maximum torque, which can be obtained. Therefore, optimum spark timing is important for the HCNG-fueled engine. The addition of hydrogen into natural gas gives the benefit of reducing the flame progress phase as compared to PNG. In this development work, the maximum torque and power performance is retained in the case of 18% HCNG, and SFC is reduced. Therefore, for the 18% HCNG blend, the spark timing is retarded towards TDC to get the benefit of hydrogen combustion. Thus, the in-cylinder pressure and RoHR curves highlight no significant variances for PNG and 18% HCNG fuels, demonstrating that, in most cases, the retarding of the spark timing balances the combustion progression in the event of hydrogen addition. Consequently, nearly identical peak firing pressures were attained.

The overall combustion data, along with the Start of Combustion (SoC), End of Combustion (EoC), and Mass Burn Fraction (MBF) for BMEP 3.74, 5.63, and 7.5 bar, are shown in Figure 7, Figure 8, and Figure 9, respectively. With the increase in engine load vis-à-vis BMEP, the fuel quantity is amplified, which burns the air-fuel mixture rapidly and leads to higher RoHR and in-cylinder temperature. With the increase in BMEP, the cumulative heat release is also increased due to the presence of hydrogen in the 18% HCNG blend. At BMEP 3.74, the 18% HCNG fuel has a peak pressure of 30.63 bar as compared to PNG, which is 28.39 bar. The SoC for the 18% HCNG blend is 4.70 degrees before TDC, and for PNG it is 3.70 degrees before TDC. Coming to the MBF part, 18% HCNG has MBF90% at 16.85 degrees after TDC, and for PNG it is 20.05 degrees after TDC. This signifies that the HCNG fuel has faster flame propagation and has a shorter phase. Similarly, at BMEP 5.63, the 18% HCNG fuel has a peak pressure of 39.60 bar as compared to PNG, which is 37.07 bar. The SoC for an 18% HCNG blend is 5.10 degrees before TDC, and for PNG it is 4.20 degrees before TDC. Coming to the MBF part, 18% HCNG has MBF 90% at 15.45 degrees after TDC, and for PNG it is 18.45 degrees after TDC. Similarly, at BMEP 7.5, the 18% HCNG fuel has a peak pressure of 53.36 bar as compared to PNG, which is 52.23 bar. The SoC for the 18% HCNG blend is 5.90 degrees before TDC, and for PNG it is 5.45 degrees before TDC. Coming to the MBF part, 18% HCNG has MBF90% at 14.10 degrees after TDC, and for PNG it is 15.40 degrees after TDC. With the increase in BMEP, the flame progress and flame development phase occurs rapidly for HCNG, as hydrogen has a smaller quenching distance and improves the thermal efficiency of the engine with higher BMEP. Also, the peak pressure increased with an increase in BMEP due to the higher fuel intake at higher engine loads.

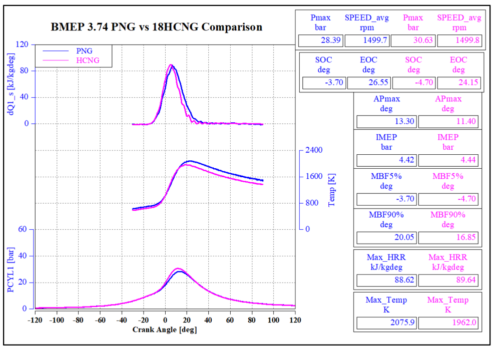

Figure 7. Combustion parameters at BMEP 3.74 bar

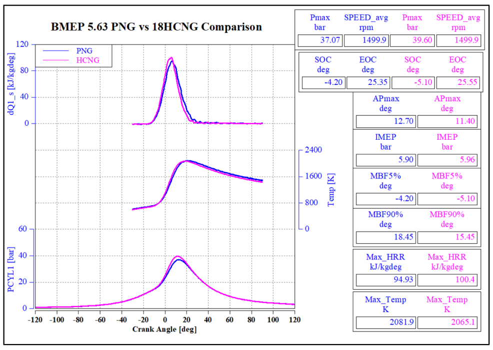

Figure 8. Combustion parameters at BMEP 5.63 bar

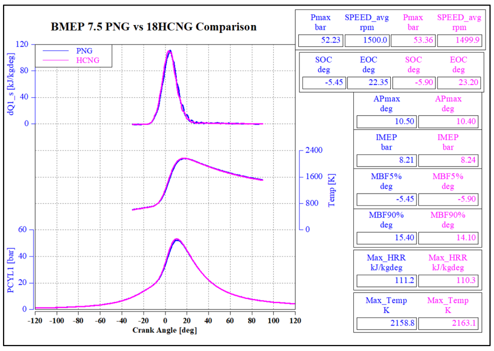

Figure 9. Combustion parameters at BMEP 7.5 bar

The combustion parameters were analysed for their significance using ANOVA techniques. The maximum in-cylinder pressure (Pmax) and 5% mass burn fraction (MBF5) were evaluated for PNG and 18HCNG blends. The ANOVA result table for Pmax and MBF5 is given in Table 8 and Table 9, respectively.

Table 8. ANOVA results for Pmax using PNG and 18HCNG

Source	DF	Adj SS	Adj MS	F-Value	P-Value
BMEP	3	553.301	184.434	8772.11	0.008
Blends	1	5.688	5.688	270.55	0.039
Error	1	0.021	0.021		
Total	5	559.123			

The P-value for BMEP is 0.008. This value is well below the common alpha level of 0.05, indicating that the effect of BMEP on Pmax is statistically significant. This suggests that as BMEP increases, Pmax increases. The

P-value for Blends is 0.039. This value is also below 0.05, indicating that the effect of the fuel blends on Pmax is statistically significant as well.

Table 9. ANOVA results for Pmax using PNG and 18HCNG

Source	DF	Adj SS	Adj MS	F-Value	P-Value
BMEP	3	2.21604	0.738681	131.32	0.064
Blends	1	0.85562	0.855625	152.11	0.052
Error	1	0.00563	0.005625		
Total	5	3.10333			

The P-value for BMEP is 0.064, which is slightly above the conventional alpha level of 0.05. This suggests that there is some evidence of a significant effect; however, it is not strong enough to reject the null hypothesis at the 5% significance level. In contrast, the P-value for Blends is 0.052, which is very close to 0.05. This indicates a statistically significant effect of the blends on the response variable, as it falls just below the threshold for significance. The ANOVA results suggest that both BMEP and Blends have significant effects on the response variable (MBF5), with Blends showing a slightly stronger significance than BMEP.

4.2 Performance Characteristics

The engine here was a constant-speed genset engine operating at 1500 rpm. The performance parameters are evaluated with PNG and 18% HCNG fuel and are shown in Figure 10. Here, the maximum torque and power performance was retained in the case of 18% HCNG. Therefore, for the 18% HCNG blend, the spark timing was retarded towards TDC to get the benefit of hydrogen combustion. From the performance graph, it can be seen that the BSFC for 18% HCNG has significantly reduced when compared to PNG. An overall reduction of 4% BSFC in the case of HCNG is observed, which denotes fuel savings while using HCNG. The reduction of BSFC symbolizes the lower fuel consumption, which gives the benefit of lesser CO_2 formation. This benefit in BSFC was validated using the ANOVA technique, and the result table for BSFC analysis is shown in Table 10.

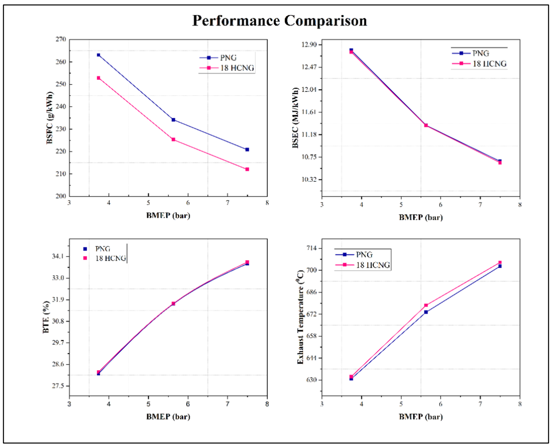

Figure 10. Performance graph comparison for PNG and 18% HCNG blend

Table 10. ANOVA results for BSFC using PNG and 18HCNG

Source	DF	Adj SS	Adj MS	F-Value	P-Value
BMEP	2	446931	223466	3203.20	0.00031
Blend	1	36449	36449	522.46	0.00190
Error	2	140	70		
Total	5	483519			

The P-value indicates the probability that the observed results could occur by random chance. A lower P-value suggests a more significant effect. The P-value associated with both the BMEP and blend factors is less than 0.05, indicating that BSFC is a significant variable. This result demonstrates that both BMEP and blend factors significantly affect BSFC, as their respective P-values also fall below the critical threshold of 0.05. Furthermore, BMEP has a considerably stronger impact than the blend factors, as illustrated by its higher F-value and lower P-value. The same trend of BSFC reduction with the HCNG blend was observed by Hora et al. [13], who reported that compared to CNG, HCNG displayed a lower BSFC at a particular BMEP. This resulted from the addition of hydrogen to HCNG, which increased its calorific value and decreased the amount of fuel used specifically for braking. Compared to CNG, HCNG requires less fuel input energy to create the same unit power output because of its increased braking thermal efficiency. The BTE is slightly higher for the 18% HCNG blend with respect to PNG due to the higher energy content of HCNG, rapid flame development, and higher flame speed. In a paper, Molina et al. [8] have said that the impact of hydrogen blending on compressed natural gas (CNG) indicates that as the fuel blend's hydrogen percentage rises, IMEP and gross indicated efficiency improve. The main reason for this improvement is the greater lambda (λ) attained because of hydrogen's unique combustion characteristics, which allow for ultralean, steady combustion. Similarly, with the benefit of BSFC, the brake-specific energy consumption (BSEC) is lower for 18% HCNG than that of PNG. The engine exhaust temperature is higher for the 18% HCNG blend, as HCNG has a more complete combustion, and adiabatic flame temperature is achieved, which increases the enthalpy of formation.

Similarly, for exhaust temperature analysis using ANOVA, the result table is shown in Table 11.

Table 11. ANOVA results for BSFC using PNG and 18HCNG

Source	DF	Adj SS	Adj MS	F-Value	P-Value
BMEP	2	1356562	678281	2291.69	0.00043
Blend	1	3528	3528	11.92	0.07462
Error	2	592	296		
Total	5	1360682			

For BMEP, the P-value is 0.00043, which is quite low and indicates that the effect of BMEP is statistically significant. The higher the BMEP levels, the higher the engine exhaust temperature will be. In contrast, for Blend, the P-value is 0.07462, which is above the 0.05 threshold. This suggests that the effect of Blend is not statistically significant at the 5% level.

4.3 Emission Characteristics

In the worldwide scenario, controlling and reducing engine-out emissions has become a challenge for research engineers. Emission norms are becoming more stringent day by day. The motto of developing this particular genset engine with HCNG is to reduce the engine's harmful emissions. In this project, a three-way catalytic converter (TWC) is mounted to reduce the emissions. The CO, HC, and CH_4 emissions are reduced for the 18% HCNG blend compared to PNG. The reduction in hydrocarbon emissions is due to a higher H/C ratio for the HCNG blend. The 18% HCNG increases the NOx emission as compared to PNG. The higher NOx formation is due to the higher in-cylinder combustion temperature, which impedes the formation of thermal NOx. The overall CO_2 emissions are reduced for the HCNG blend as compared to PNG due to the lower carbon content in the HCNG fuel. The emissions results for different BMEPs are shown in Figure 11. The CO emission is significantly reduced and analysed using ANOVA. The result table for CO emissions is given in Table 12.

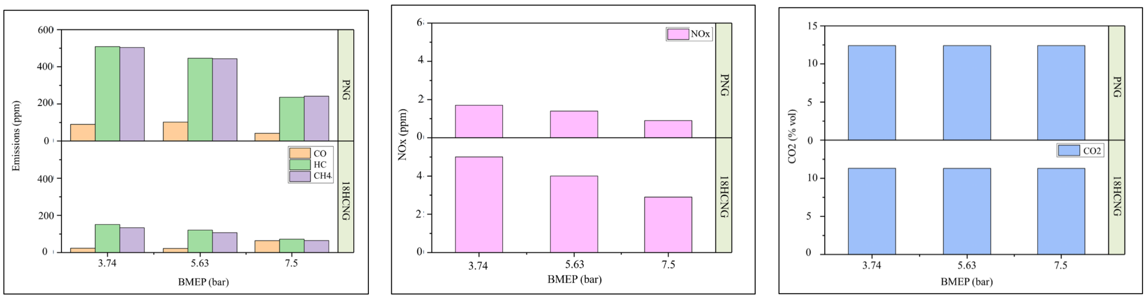

Figure 11. Raw emissions comparison at different BMEP for PNG and 18% HCNG fuels

Both P-values suggest that neither "Blends" nor "BMEP" has a statistically significant effect on CO at the conventional alpha level of 0.05. This suggests that variations in CO may be due to other factors, such as higher flame speed, which is reflected in the 5% mass burn fraction of the air-fuel mixture (MBF5). The ANOVA result table for MBF5 is given in Table 9. The ANOVA results suggest that both BMEP and Blends have significant effects on the response variable (MBF5), with Blends showing a slightly stronger significance than BMEP. This explains the reason for the reduction of CO emissions in the HCNG blend.

Table 12. ANOVA results for BSFC using PNG and 18HCNG

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Blends	1	2629.65	2629.65	1.70	0.32178
BMEP	2	84.20	42.10	0.03	0.97345
Error	2	3087.22	1543.61		
Total	5	5801.07			

The NOx emissions for the HCNG blend have increased. The reason for the increase is due to the increase in the combustion temperature. The ANOVA result table for the combustion temperature is given in Table 13.

Table 13. ANOVA results for NOx using PNG and 18HCNG

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Blends	1	10.3606	10.3606	50.95	0.01907
BMEP	2	2.1409	1.0704	5.26	0.15963
Error	2	0.4067	0.2033		
Total	5	12.9082			

The P-value for Blends is 0.01907. This value is below the common alpha level of 0.05, indicating that the effect of Blends on NOx emissions is statistically significant. This suggests that HCNG fuel blends contribute to higher levels of NOx emissions. In contrast, the P-value for BMEP is 0.15963. This value exceeds the 0.05 threshold, indicating that the effect of BMEP on NOx emissions is not statistically significant at the 5% level. While there may be some variation in NOx emissions due to BMEP, the ANOVA results show that the type of fuel blend significantly affects NOx emissions, as evidenced by the low P-value (0.01907) and the high F-value of 50.95. Conversely, the effect of BMEP on NOx emissions is not statistically significant, as reflected by the higher P-value (0.15963).

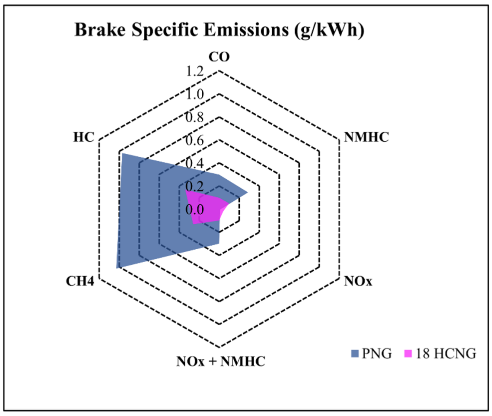

Figure 12. Brake Specific emissions comparison for CPCB IV+ Cycle

The brake-specific emissions are calculated using the ugas constant derived for HCNG fuel by the work carried out by Bandyopadhyay et al. [36]. As per the CPCB IV+ legislature, the blow-by gas for the engine above 58 kW power rating can not be released in atmosphere. Therefore, a Close Crankcase Ventilation (CCV) system is also used to bypass the blow-by gases back to the air-intake system. The selection of CCV or OCV is done based on the literature work done by Sutar et al. [37]. The brake-specific emission is shown in Figure 12. The engine tested with 18% HCNG has complied with CPCB IV+ norms. The emissions are well within the legislation limit and the limit with the deterioration factor. The cycle-out engine emission is reduced for the 18% HCNG blend, where brake-specific CO emission is observed to be reduced by 66%, brake-specific NMHC emission is reduced by 65%, brake-specific CH_4 emission is reduced by 74%, and brake-specific HC emission is reduced by 64% when compared to PNG. The NOx emission is increased in the case of the 18% HCNG blend and was found to be increased by four times when compared to PNG fuel.

4.4 Endurance Outcome

After the emission and performance trial with an 18% HCNG blend, the engine is taken for an endurance test for 100 hours with an 18% HCNG blend. The performance parameters are monitored pre- and post-endurance tests and found within a drop of 1%, which is well within the OEM acceptable limits.

5 Conclusion

1. The development trial of 18% HCNG fuel on Power Generator is proved to be successful, and in-use PNG gensets can be converted to HCNG to meet CPCB IV+ norms without any major changes in the fuel system, facilitating its adoption across various sectors without significant infrastructure overhauls.

2. Considering directives of CAQM in New Delhi, India, the introduction of the HCNG Power Generating Set will be more useful in converting the in-use CPCB II genset to CPCB IV+ without investing much in after-treatment devices.

3. Regulated emissions are under the legislative limit with the 18% HCNG blend for CPCB IV+ limits. This is India's First HCNG genset engine certified for CPCB IV+ emission norms.

4. CO, CH_4 and HC emissions are drastically reduced in the case of the 18% HCNG fuel by 66%, 74% and 65% respectively, this is due to the lower carbon-to-hydrogen ratio for HCNG. The overall carbon reduction leads to a step towards carbon footprint reduction with the use of HCNG.

5. As a part of development, smoke and particulate emissions were also measured during the trial and are found to be negligible. From the literature study, it was found that the partial combustion of lubricating oil forms nano-particles which contribute to the particulate matter emissions in the exhaust [38].

6. The BSFC for the HCNG blend is reduced as compared to the PNG. Overall, the fuel economy was improved by 4% compared to PNG.

7. The BTE was improved for the 18% HCNG blend due to the rapid combustion process and higher enthalpy of formation during combustion.

8. Combustion in SI engines has three discrete combustion stages, viz. flame progress, flame propagation, and after-burning. Here in the case of the 18% HCNG blend, the flame progress phase is shortened, and the MBF5% is achieved quicker over the crank angle as compared to PNG, which leads to rapid combustion, and a higher magnitude of peak firing pressure is obtained. The after-burning period that is after MBF90% is subsequently reduced for 18% HCNG as compared to PNG, which contributes lesser unburned emissions.

9. The flame development phase is shortened due to the presence of hydrogen in CNG, which significantly lowers the ignition energy prerequisite of hydrogen, which is directed to the rapid formation of OH radicals during combustion. Similarly, the crank angle position for MBF90% was also retarded towards TDC for the 18% HCNG blend due to the higher flame speed of hydrogen and higher in-cylinder pressure achieved.

10. The statistical verification from ANOVA indicates that engine performance parameters, such as BSFC and exhaust temperature, are significantly affected by engine BMEP levels. In contrast, emissions like CO and NOx are greatly influenced by fuel blends.

11. As the hydrogen content in the HCNG blend increases, the burning rate improves accordingly, which enhances the likelihood of knocking. Elevated levels of hydrogen in CNG can lead to irregular combustion traits, such as knocking, backfiring, or pre-ignition, and can also result in decreased engine efficiency.

12. The drop in performance parameters is within 1% after the endurance trial of 100 hours with 18% HCNG.

13. Existing 62.5 KVA CPCB II CNG Gensets available in the market can be converted (retrofitment with a low-cost solution) to CPCB IV+ with flashing of developed calibration strategy with supply of HCNG.

14. As diesel generators are increasingly scrutinized for their environmental impact, HCNG presents a viable alternative that aligns with the industry's transition towards cleaner technologies without the use of Retro-fitable Emission Control Devices (RECD).

15. The future pathway of HCNG in the Indian Power Generator market appears promising as the country increasingly seeks sustainable energy solutions. HCNG, which blends hydrogen with CNG, offers several environmental benefits, making it an attractive alternative fuel for power generation.

16. The Indian government has recognized HCNG as a viable fuel option since September 2020, facilitating its introduction in various applications, including public transportation. The Delhi government initiated trials using HCNG in buses, which demonstrated significant reductions in emissions and improved fuel efficiency.

17. Indian Oil Corporation (IOCL) has pioneered the compact reforming process to produce HCNG, which simplifies the blending of hydrogen and CNG. This technology is crucial for scaling up HCNG production and usage in various sectors, including genset applications.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare no conflict of interest.

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Nomenclature

BIS	Bureau of Indian Standard
BMEP	Brake Mean Effective Pressure
CAG	Compound Annual Growth Rate
CAQM	Commission for Air Quality Management
CCV	Closed Crankcase Ventilation
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
ECU	Electronics Control Unit
HC	Hydrocarbon
NMHC	Non-Methane Hydrocarbon
NOx	Oxides of Nitrogen
OCV	Open Crankcase Ventilation
OEM	Original Equipment Manufacturer
PNG	Piped Natural Gas
RoHR	Rate of Heat Release
RTD	Resistance Temperature Detector
SFC	Specific Fuel Consumption
USP	Unique Selling Point