Date of publication April 14, 2025, date of current version April 14, 2025.
Digital Object Identifier ***10.21608/pesj.2025.369010.1018***

PHAROS ENGINEERING SCIENCE JOURNAL

Strategies for Optimizing Efficiency and Reducing Emissions Footprint in Spark Ignition Engine Power Plants Using Ethanol and CNG

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Abstract: This study investigates strategies to enhance the efficiency of Spark Ignition (SI) engine power plants while simultaneously reducing their emissions footprint through alternative fuels, specifically ethanol and compressed natural gas (CNG). As global energy demands continue to rise and environmental concerns intensify, optimizing SI engine performance has become imperative. This research adopts a comprehensive approach that integrates advanced design modifications, fuel optimization, and innovative operational strategies to minimize emissions. Numerical findings demonstrate that implementing enhanced combustion chamber designs and optimized fuel injection systems can lead to a thermal efficiency increase of up to 15%, elevating baseline thermal efficiency from 25% to 40%. The adoption of alternative fuels such as ethanol and CNG significantly reduces greenhouse gas emissions; ethanol blends achieve up to 30% lower CO2 emissions compared to conventional gasoline, decreasing emissions from 2.31 kg CO2 per liter of gasoline to 1.61 kg CO2 per liter of ethanol. In contrast, CNG shows even greater potential for reducing the emissions footprint, with CO2 emissions as low as 0.18 kg CO2 per megajoule, significantly lower than those from traditional fuels. Additionally, the introduction of smart control systems and predictive maintenance strategies results in a 20% reduction in operational downtime, from 15% to 12% of total operational time, contributing to a 10% overall efficiency improvement.

Keywords: SI engine performance; CNG engine; Engine emissions; Alternative fuels

1. Introduction:

The global demand for sustainable energy solutions is increasingly critical, particularly in the power generation sector, where traditional fossil fuel-based plants significantly contribute to carbon emissions and climate change [1-5]. The transition to cleaner energy sources is essential, with gas turbines (GT) emerging as pivotal due to their high thermal efficiency and adaptability to alternative fuels like hydrogen and ammonia, which can reduce CO2 emissions by up to 100% in specific models[6-13]. Integrating renewable energy sources with effective energy management strategies can substantially lower greenhouse gas emissions while providing economic benefits[14]. Additionally, supercritical CO2 power generation technologies present a promising avenue for enhancing efficiency and reducing environmental impact. A robust policy framework is also necessary to support this transition, promoting technological innovation and equitable access to sustainable solutions [15-17].

Reducing emissions in power generation relies on technologies like carbon capture and renewable energy integration. Gas turbines (GT) are being modified to use cleaner fuels such as natural gas, hydrogen, and ammonia, significantly lowering CO2 emissions in specific models[6, 18-20]. Carbon capture and storage (CCS) technologies are also being implemented in coal-fired plants to reduce their environmental impact. Renewable energy sources like wind and solar, alongside energy storage, enhance grid stability and support a resilient energy infrastructure [21-23]. These advancements are crucial for addressing climate change and ensuring a sustainable energy future. Emissions from traditional fuels in spark ignition engines contribute to air pollution, releasing harmful pollutants like carbon monoxide, nitrogen oxides, and hydrocarbons, posing serious health risks. Urbanization exacerbates these challenges, driving the need for alternative fuels like biomass, hydrogen, and methanol, which can mitigate emissions. Additionally, advancements in engine technology, such as cylinder deactivation strategies, show promise in enhancing fuel efficiency and reducing emissions. Transitioning to cleaner energy sources and improving technologies are critical for addressing the adverse effects of fossil fuel reliance on health and the environment [24-28].

Biofuels, hydrogen, and electric options are emerging as viable replacements for spark ignition engines, each with unique benefits and challenges. Biofuels, derived from agricultural waste and algae, lower reliance on fossil fuels, though large-scale production remains complex [29-33]. Green hydrogen produced from renewable sources presents a promising solution, though its production and storage pose economic and technical challenges. Studies indicate that hydrogen blends with gasoline can enhance combustion efficiency and reduce emissions in these engines. Prioritizing these cleaner solutions can lead to substantial environmental and public health benefits [34-37]. Ethanol and compressed natural gas (CNG) are recognized for their environmental benefits in spark ignition engines. Ethanol, derived from renewable biomass, enhances combustion efficiency, leading to lower emissions, and is biodegradable and non-toxic[6]. Studies suggest increasing ethanol content in biofuels can improve thermal efficiency and knock resistance, though it may increase nitrogen oxides and hydrocarbons in certain conditions [14]. Similarly, CNG, primarily composed of methane, offers cleaner combustion with significantly lower nitrogen oxides and minimal particulate matter[15]. The integration of ethanol as an alternative fuel in power plants presents significant environmental and operational advantages, particularly in the context of sustainable energy transitions. Ethanol, characterized by a lower carbon footprint and higher energy density compared to traditional fossil fuels can enhance combustion efficiency and reduce harmful emissions, such as carbon monoxide and unburned hydrocarbons. Studies indicate that ethanol-blended fuels can improve thermal efficiency and reduce fuel consumption in power generation systems, aligning with the goals of a circular bio-economy. Furthermore, the optimization of ethanol-powered internal combustion engines has demonstrated substantial increases in brake power and thermal efficiency, alongside notable reductions in greenhouse gas emissions. However, the economic feasibility of retrofitting existing power plants to utilize ethanol will largely depend on local fuel availability and infrastructure costs, necessitating careful consideration of these factors in operational planning [5] [38, 39].

To optimize ethanol and CNG as fuels, precise tuning of engine parameters, including ignition timing and fuel injection strategies, is necessary. Research shows integrating artificial neural networks with response surface methodology can improve the efficiency of ethanol engines, achieving up to 29.8% increases in brake thermal efficiency and reducing CO and hydrocarbons significantly[40]. Dual-fuel systems, such as CNG and ethanol, have shown improved combustion characteristics, leading to reduced emissions and enhanced performance[41]. These alternative fuels not only lower carbon footprints but also align with sustainable energy goals[42]. Ethanol and CNG also provide economic sustainability. Ethanol, derived from crops like corn and sugarcane, supports rural job creation and contributes to greenhouse gas reduction, with studies showing up to a 54% decrease in emissions when used in transportation. CNG, being cheaper than traditional fuels, offers substantial savings, especially in the public transportation and logistics sectors. Both fuels can be integrated into existing engine technologies with minimal modifications, lowering the investment for adoption. By prioritizing these alternative fuels, countries can enhance energy independence, stimulate economic growth, and address pressing environmental challenges [43-48].

Overall, the transition to alternative fuels like ethanol and CNG represents a promising step toward a sustainable energy future. CNG offers lower carbon emissions and higher knock resistance, achieving performance comparable to gasoline engines with optimized injection strategies. Ethanol, particularly in high blends, improves combustion efficiency and reduces pollutants, though it may increase CO2 emissions due to higher fuel consumption. Both fuels present advantages in production costs and potential savings, though infrastructure challenges remain for widespread adoption. This transition is crucial for a sustainable energy future.

2. Background and Previous Studies on Alternative Fuels and SI Engine Modifications:

Spark ignition (SI) engines, widely utilized in automobiles and machinery, operate on a four-stroke cycle comprising intake, compression, power, and exhaust strokes, with performance heavily influenced by fuel type, air-fuel mixture, and ignition timing. Recent studies highlight the potential of alternative fuels, such as compressed biomethane gas (CBG) and alcohols, which can enhance fuel efficiency and reduce emissions; for instance, CBG demonstrated a maximum brake thermal efficiency (BTE) of 23.33% and lower emissions compared to traditional fuels[40] [49, 50]. The future of SI engines is projected to focus on improving performance and utilizing cleaner fuels, addressing both efficiency and environmental concerns [41, 51-53]. Additionally, the variability in combustion characteristics of alternative fuels necessitates robust ignition systems to maintain performance while minimizing spark plug [42, 54-56]. Overall, advancements in fuel technology and engine design are crucial for optimizing SI engine performance and sustainability[57-59].

Fuel types significantly influence the performance and emissions of spark ignition (SI) engines, with gasoline being the most prevalent due to its high energy content and ease of evaporation. However, alternative fuels like ethanol, methanol, and compressed biomethane gas (CBG) are gaining traction for their potential to reduce greenhouse gas emissions and improve fuel efficiency. Ethanol, while having a high octane rating, presents challenges such as lower calorific value and corrosiveness, which can be mitigated by blending it with diesel, resulting in improved brake-specific fuel consumption (BSFC) and reduced emissions[60]. Methanol, despite its higher consumption rates and toxicity, shows promise in certain blends but is less favorable compared to ethanol[6] [61-63]. CBG has demonstrated superior performance metrics, achieving a maximum brake thermal efficiency (BTE) of 23.33% and lower emissions compared to other fuels[40]. The combustion characteristics are also affected by factors like ignition timing and air-fuel ratios, which are critical for optimizing engine performance and minimizing pollutants[64]. Ethanol and compressed natural gas (CNG) are increasingly recognized as viable alternatives to gasoline in spark ignition engines, each presenting unique benefits and challenges. Ethanol, a renewable biofuels with a high octane rating, enhances engine performance by allowing higher compression ratios, which can improve thermal efficiency and reduce emissions of certain pollutants, such as hydrocarbons and carbon monoxide[65]. However, its lower energy density compared to gasoline can lead to increased fuel consumption[6]. Conversely, CNG offers a cleaner combustion profile, significantly lowering greenhouse gas emissions and allowing for leaner combustion strategies that enhance efficiency, particularly at partial loads[66]. While CNG demonstrates lower NOx emissions under certain conditions, it may require additional after-treatment systems to meet stringent regulations. Both fuels contribute to reducing dependence on fossil fuels, supporting sustainability efforts, yet their adoption is hindered by infrastructure limitations and varying performance characteristics across different engine configurations[67].

Compressed Natural Gas (CNG) is increasingly recognized as a cleaner and more efficient alternative to traditional fuels like gasoline and ethanol, primarily due to its lower emissions and higher thermal efficiency. CNG combustion results in significantly reduced levels of carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter, thereby enhancing air quality[68]. Its superior anti-knock properties and adaptability to existing engine technologies allow for improved performance, with studies indicating that CNG engines can achieve comparable brake mean effective pressure (BMEP) to gasoline engines while emitting fewer pollutants. Furthermore, CNG's abundant availability in many regions supports its accessibility as a fuel option, although infrastructure development remains a challenge in some areas. Overall, the combination of environmental benefits and operational efficiency positions CNG as a compelling choice for reducing emissions and enhancing engine performance in the transportation sector[69].

The efficiency and emissions of spark ignition engines are significantly influenced by various factors, including engine configuration, operating conditions, and fuel characteristics. Multi-cylinder engines generally provide smoother operation and enhanced power output, yet they may struggle with fuel consumption and emissions at lower loads[70]. Advanced technologies such as variable valve timing (VVT) and turbocharging optimize combustion processes, improving both efficiency and emissions by adjusting valve timing and enhancing air-fuel mixing[71]. Additionally, higher compression ratios can lead to improved thermal efficiency but may complicate emissions control due to increased combustion temperatures[72-74]. Experimental studies indicate that strategies like cylinder deactivation can yield fuel economy improvements of up to 10.8% under low load conditions[70], while the use of alternative fuels, such as methanol blends, has been shown to effectively reduce harmful emissions[75]. Overall, the integration of these advanced configurations and fuel strategies is crucial for enhancing the performance and environmental impact of spark ignition engines.

Operating conditions, such as load, speed, and temperature, significantly influence engine efficiency and emissions across various engine types. Higher loads and speeds typically enhance combustion completeness, improving efficiency but potentially increasing nitrogen oxides (NOx) and particulate matter emissions if not managed properly[76]. Conversely, lower loads can lead to incomplete combustion, resulting in elevated carbon monoxide (CO) and hydrocarbon (HC) emissions[77] [78-80]. Fuel characteristics, including energy density and octane ratings, are crucial; for instance, higher octane fuels like ethanol enable higher compression ratios, enhancing efficiency and reducing knocking while lowering emissions[81]. However, fuels with lower energy density may necessitate engine recalibration to optimize performance without exacerbating emissions. Advanced emissions control technologies, such as exhaust gas recirculation (EGR) and catalytic converters, are essential for minimizing harmful emissions and maximizing efficiency under varying operational conditions[77].

Compressed Natural Gas (CNG) has emerged as a viable alternative fuel for improving engine efficiency and reducing emissions, primarily due to its high methane content, which facilitates cleaner combustion compared to gasoline. Studies indicate that CNG-powered engines exhibit significantly lower emissions of carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter, with some configurations achieving emissions levels comparable to those of pure gasoline engines. Engine modifications, such as optimized ignition timing and advanced injection strategies, have been shown to enhance performance and reduce fuel consumption. Additionally, the integration of dual-fuel systems, combining CNG with ethanol or gasoline, has been explored to leverage the benefits of both fuels, resulting in improved combustion characteristics and lower emissions. Despite challenges like energy density and infrastructure needs, innovations in engine design and emission control systems are pivotal for maximizing the sustainability of spark-ignition engines using CNG.

3. Methodology of using and testing ethanol and compressed natural gas (CNG) in spark ignition engines:

The methodology for testing ethanol and compressed natural gas (CNG) in spark ignition engines involves establishing a controlled experimental environment to evaluate the fuels' properties, including energy content and emissions profiles. These factors are critical for assessing both efficiency and environmental impact. Research indicates that CNG offers advantages such as a high-octane number and lower emissions, making it a viable alternative to traditional fuels. The combustion characteristics of a direct-injection natural gas engine under various fuel injection timings were investigated. The results showed that fuel injection timing had a large influence on the engine performance, combustion, and emissions and these influences became largely in the case of late injection. Over-late injection would supply insufficient time for the fuel-air mixing of the late part of the injected fuel, bringing poor quality of mixture formation and subsequently resulting in a slow combustion rate, long combustion duration, and high HC concentration. As shown in **Figure 1,** multi-fuel can be used to enhance the combustion of diesel engines [82].

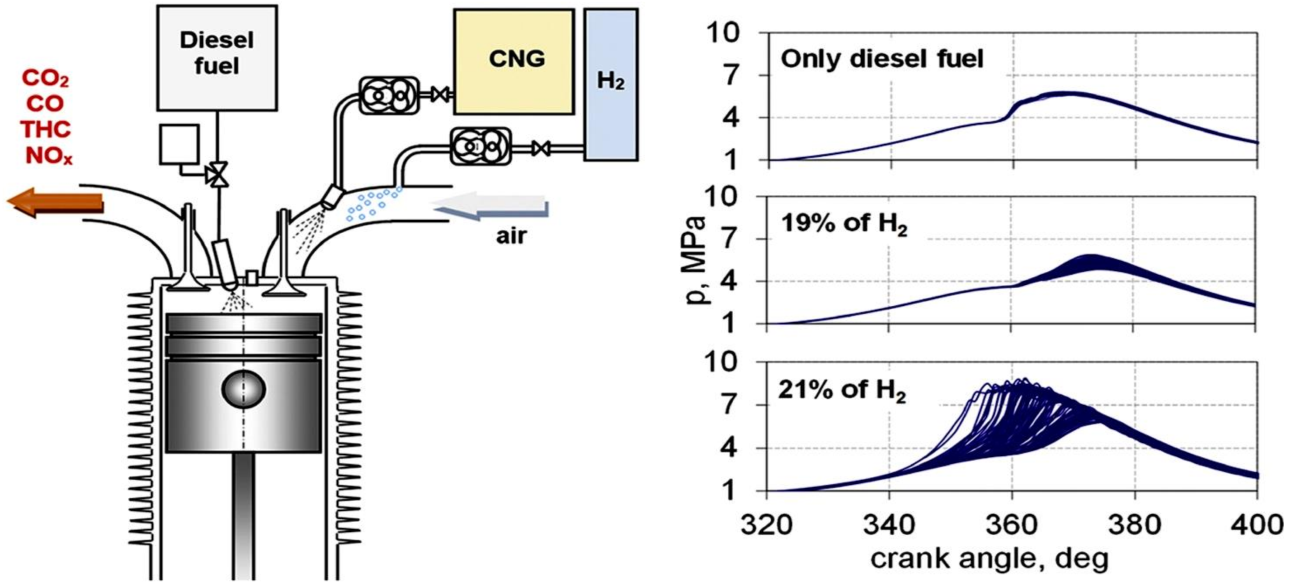

Figure1 **Impact of hydrogen-enriched natural gas on the combustion behavior and emission characteristics of a dual-fuel diesel engine[82].**

Ethanol was utilized in advanced combustion modes like homogeneous charge compression ignition (HCCI), demonstrates improved fuel conversion efficiency and reduced combustion duration. Additionally, studies show that varying fuel mixtures, including ethanol and CNG, significantly influence combustion characteristics and emissions, with optimal ratios enhancing performance metrics such as brake thermal efficiency and reducing harmful emissions like CO and unburnt hydrocarbons. Thus, a comprehensive understanding of these fuel characteristics under controlled conditions is essential for reliable and repeatable results in performance assessments.

Key performance metrics for assessing efficiency and emissions in ethanol and CNG fuel testing include thermal efficiency and brake-specific fuel consumption (BSFC). Thermal efficiency indicates how effectively an engine converts fuel into work, with studies showing that ethanol-biodiesel operations can achieve up to 34.92% higher thermal efficiency compared to baseline diesel operations [3]. BSFC, which measures fuel usage relative to power output, has been reported to decrease by 3% with increasing ethanol blends in gasoline, indicating improved fuel economy [4]. Additionally, the use of CNG in dual-fuel modes has demonstrated significant reductions in emissions, particularly NOx and particulate matter, while maintaining competitive thermal efficiency [5]. Overall, the integration of ethanol and CNG fuels not only enhances engine performance but also contributes to lower emissions, aligning with global sustainability goals [6]. Optimization techniques significantly enhance the performance of ethanol and CNG in spark ignition engines through methods such as engine tuning and fuel blending. Engine tuning involves adjusting parameters like air-fuel mixture, ignition timing, and valve timing to maximize efficiency and power output, as demonstrated in studies showing improved brake thermal efficiency and reduced emissions with optimized settings. Fuel blending, particularly with ethanol and CNG, allows for the exploration of various ratios to achieve optimal combustion characteristics; for instance, ternary blends of alcohols with gasoline have shown substantial improvements in performance metrics and emissions reduction. Additionally, the integration of machine learning techniques has facilitated the prediction and optimization of combustion parameters, further enhancing the operational efficiency of dual-fuel systems. Overall, these optimization strategies contribute to better engine performance and lower environmental impact. The total amount of CO2 emissions, including those associated with land use changes; highlight the contribution of Latin America and the Caribbean to total global emissions of CO2 as shown in **Figure [2] [83].**

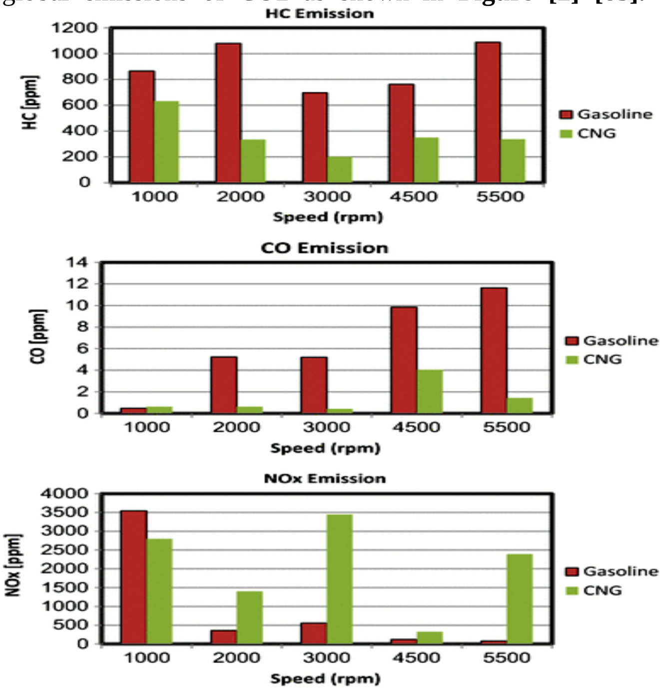

Figure 2 the emissions of the engine at gasoline and CNG-dedicated modes [83].

Although it may produce higher nitrogen oxides and hydrocarbons compared to gasoline, CNG can enhance fuel economy. However, its lower energy density often results in reduced power output unless engine modifications, such as direct injection, are implemented to optimize combustion and increase volumetric efficiency. Studies indicate that CNG can achieve significant emissions reductions, particularly in dual-fuel configurations with diesel, where it lowers NOx and smoke opacity. However, challenges remain, including the need for infrastructure development and further research on intelligent control systems to maximize CNG's potential in various engine types. Figure [3] Optimization strategies, including adjustments to the air-fuel ratio, spark timing, and combustion chamber modifications, significantly enhance engine performance and efficiency. Fine-tuning the air-fuel ratio is crucial for improving fuel combustion, which leads to increased power output and reduced fuel consumption, particularly for alternative fuels that benefit from complete combustion [5]. Modifications to the combustion chamber design can also improve brake thermal efficiency and reduce emissions by optimizing turbulence and heat transfer rates [6]. Experimental studies have shown that strategies such as cylinder deactivation can yield fuel economy improvements of up to 10.8% under specific conditions [5]. Furthermore, systematic methodologies employing the design of experiments have been developed to identify optimal engine calibrations that minimize emissions while maximizing efficiency [7]. Overall, these optimization strategies were collectively contributing to more sustainable engine operation and reduced environmental impact [8]. Figure [3] shows the Main effect plots of a signal-to-noise ratio of chip thickness ratio, b means of chip thickness ratio.

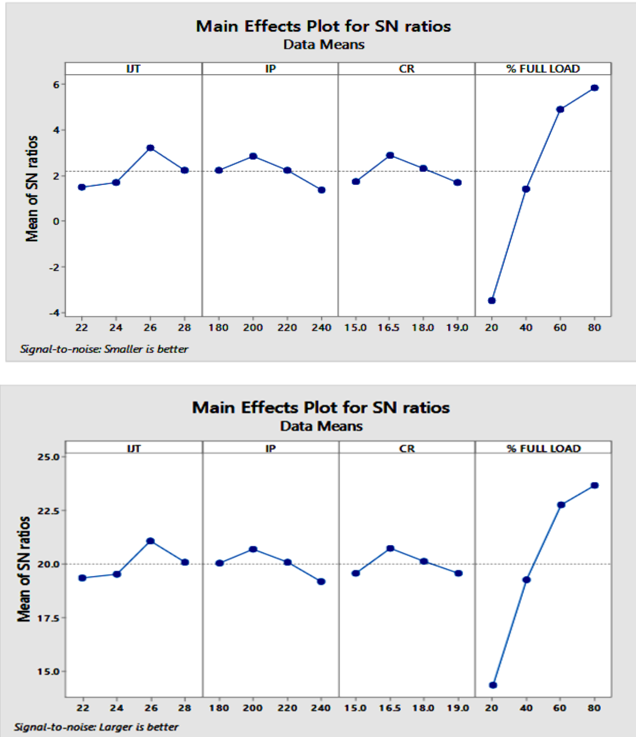

Figure3 Main Effects Plot for S/N ratios for[60]

4. Strategies for Further Optimization:

Blending ethanol with Compressed Natural Gas (CNG) presents a promising strategy for enhancing engine performance and reducing emissions. Ethanol's high oxygen content can improve combustion efficiency when combined with CNG's clean-burning characteristics, leading to a more complete fuel burn and reduced engine knock. Studies indicate that increasing the ethanol substitution rate in dual-fuel systems can enhance thermal efficiency and brake mean effective pressure, thereby improving power output and fuel economy [1]. Furthermore, under lean-burn conditions, the combination of CNG direct injection and ethanol port injection has been shown to stabilize combustion, reduce harmful emissions like CO and NOx, and optimize torque and pressure dynamics [2]. Overall, the integration of ethanol with CNG not only supports better engine performance but also contributes to lower greenhouse gas emissions, aligning with global sustainability goals.

Various tests on a four-cylinder water-cooled engine have been achieved to obtain experimental data. In addition, we partially modified the fuel supply system so that it could achieve compressed nature gas direct injection and allow ethanol to be supplied through the original port injection system. The detailed schematic diagram of the experimental device is shown in **Figure [4]**.

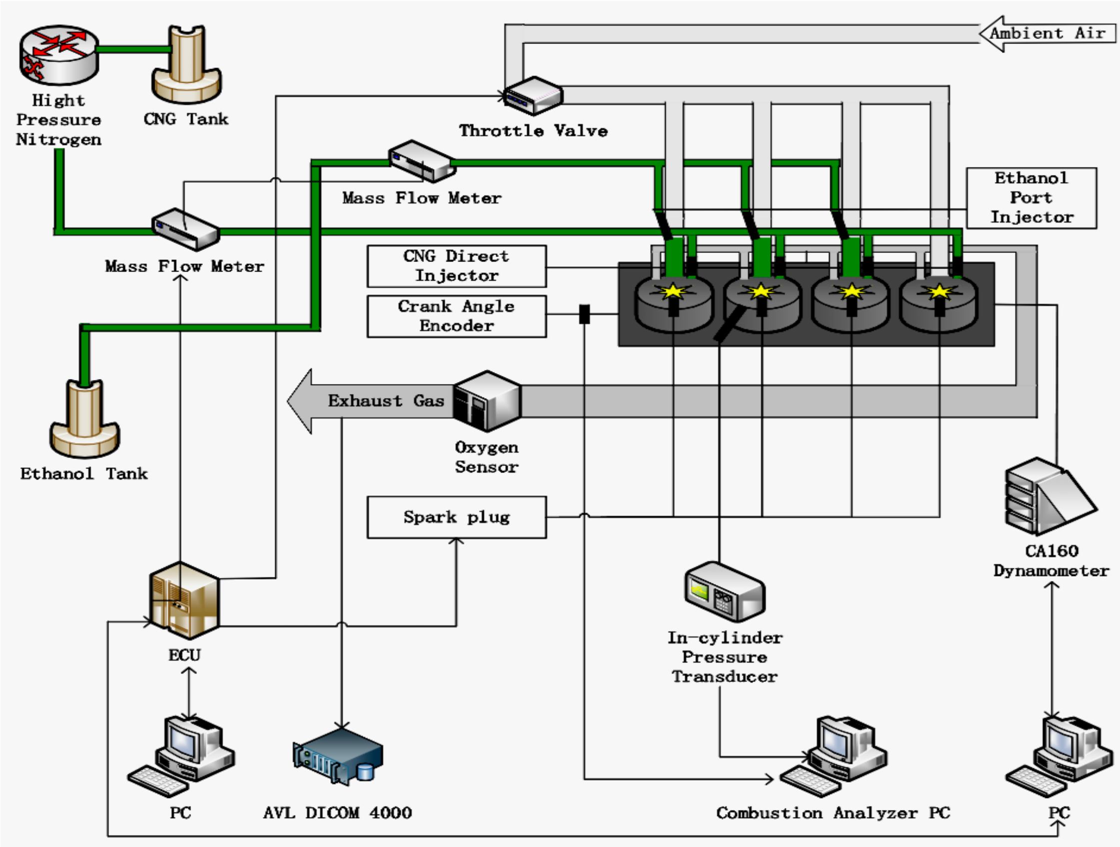

Figure 4 Experimental arrangement for testing the effect of CNG direct injection with ethanol port injection [6]

Advanced engine technologies such as direct injection (DI), turbocharging, and variable valve timing (VVT) significantly enhance the performance of engines utilizing alternative fuels like compressed natural gas (CNG) and ethanol. DI facilitates precise fuel delivery, leading to improved combustion efficiency and reduced emissions, particularly in CNG/gasoline dual-fuel engines, where optimal injection strategies can match the brake mean-effective pressure (BMEP) of traditional gasoline engines. Turbocharging complements this by increasing air intake, which is crucial for burning lower energy-density fuels, thus improving fuel economy and power output. Additionally, VVT optimizes valve timing to enhance torque across various RPMs, further supporting the effective use of alternative fuels. Studies indicate that using high alcohol content blends can improve combustion processes, although they may lead to increased fuel consumption and CO_2 emissions. Overall, these technologies collectively mitigate the limitations of alternative fuels, promoting their viability in modern engines [1].

Optimizing operational conditions such as load factors, engine speed, and temperature is critical for enhancing engine efficiency and minimizing emissions. Diesel engines, for instance, achieve optimal performance at approximately 94-95% of full load, where they exhibit improved brake thermal efficiency (40.7%) and significantly lower emissions of CO_2 (124.85 $g{\cdot}kWh^{-1}$) and unburned hydrocarbons (0.009 $g{\cdot}kWh^{-1}$). Similarly, gasoline compression ignition engines benefit from high loads, where specific injection strategies can further reduce emissions while maintaining efficiency. Moreover, employing advanced technologies like two-stage turbocharging and optimizing fuel characteristics can enhance combustion efficiency and reduce nitrogen oxide emissions, particularly under high-load conditions. Overall, maintaining higher load factors ensures more complete combustion is thereby reducing pollutants and improving fuel efficiency across various engine types.

5. Case Studies or Simulation Results:

The adoption of ethanol and compressed natural gas (CNG) in power plants, exemplified by Brazil's Green Power Plant, highlights the significant benefits and challenges associated with alternative fuels. Ethanol, derived from sugarcane, has enabled the facility to achieve over a 70% reduction in carbon emissions compared to fossil fuels, highlighting its potential for sustainable energy production. The plant's dual use of ethanol in gas turbines and steam boilers not only enhances energy output but also diminishes reliance on fossil fuels, aligning with global trends toward renewable energy sources. Furthermore, the economic feasibility of ethanol production in Brazil, supported by local agricultural practices, underscores the viability of biofuels as a cost-effective energy solution. However, challenges such as production costs and technological advancements remain critical for the broader implementation of biofuels in the energy sector [11].

The Brazilian ethanol industry exemplifies the successful deployment of alternative fuels, significantly enhancing efficiency and reducing greenhouse gas emissions. Ethanol, primarily derived from sugarcane, offers a nearly carbon-neutral fuel cycle, as the CO_2 emitted during combustion is offset by the CO_2 absorbed during the crop's growth [12]. This transition to biofuels has led to substantial reductions in carbon emissions, with Brazil's flex-fuel vehicles contributing millions of tons of reductions annually [13]. Studies indicate that bioethanol can reduce emissions by approximately 54% compared to fossil fuels [14]. Furthermore, the strategic expansion of ethanol production, particularly through cellulosic biorefineries, can meet future demands while minimizing land-use change impacts. Overall, these initiatives not only promote cleaner air but also enhance fuel efficiency, making ethanol-powered vehicles competitive with traditional gasoline options [8].

Local production capabilities, conversion costs, and operational savings significantly influence the economic feasibility of utilizing ethanol in existing power plant infrastructure. In Brazil, where sugarcane is abundantly cultivated, ethanol production is economically viable, with studies indicating that it can reduce greenhouse gas emissions by 28% compared to petrol [15]. The integration of biogases for cogeneration enhances energy efficiency, with net energy ratios reaching up to 0.984 when optimized [16]. Additionally, the potential of vinasse biogas as a renewable energy source offers substantial cost reductions and emissions savings, further supporting the transition to renewable fuels [17]. However, the scalability of ethanol production is contingent upon infrastructure adjustments and government support, particularly in regions with less established biofuels industries [18]. Overall, the combination of local feedstock availability and supportive policies can enhance the economic viability of ethanol in power generation.

Figure [5] shows the Sizes of electrolyzes, methanol synthesis, solar PV, wind power, and storage installations. The figure shows the sum of all installed capacities at all locations in the solar–wind scenario. PV photovoltaics.

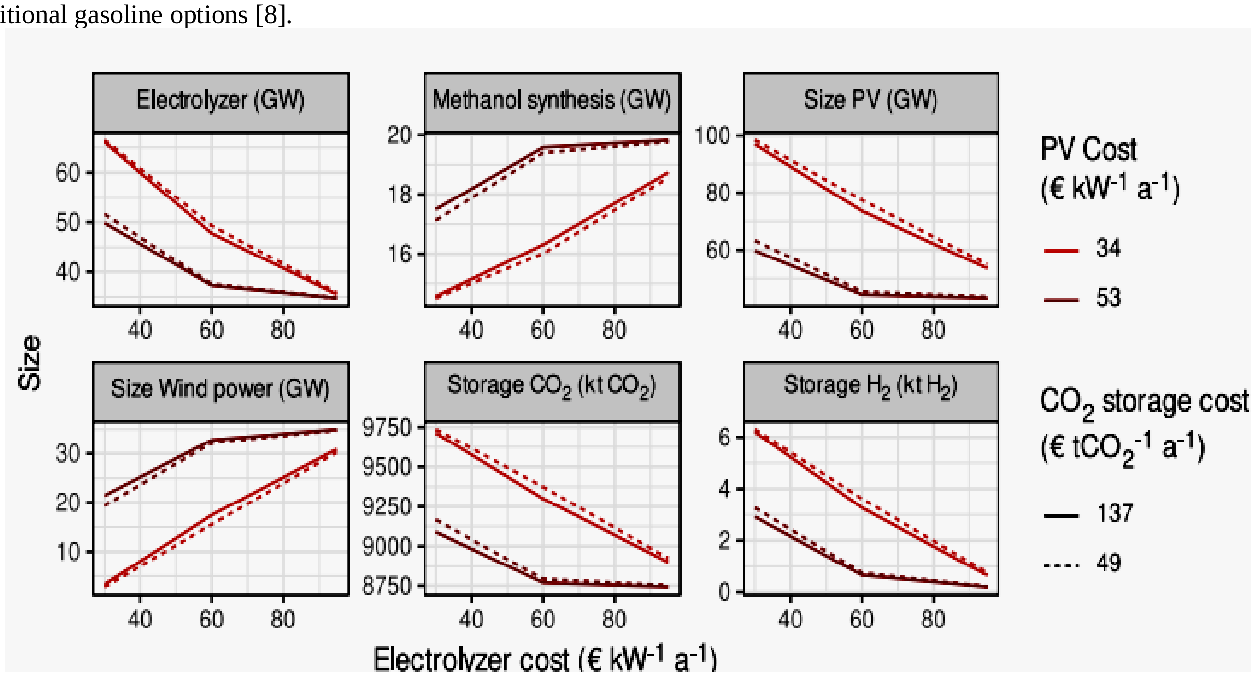

Figure 5 shows the Sizes of electrolyzes, methanol synthesis, solar PV, wind power, and storage installations [75]

7. Conclusion:

The findings underscore the importance of a holistic approach that combines innovative designs, the utilization of cleaner fuels like ethanol and CNG, and advanced operational techniques to significantly enhance the efficiency and sustainability of SI engine power plants. This research contributes to the transition towards more environmentally friendly energy solutions while ensuring reliable and efficient power generation, ultimately reducing the emissions footprint of SI engines. The study underscores the significant potential of ethanol and compressed natural gas (CNG) as alternative fuels, particularly in enhancing engine efficiency and reducing emissions across transportation and power generation sectors. Ethanol, characterized by its high oxygen content, improves combustion efficiency, leading to reduced emissions of harmful pollutants such as carbon monoxide and particulate matter, although its lower energy density may result in higher fuel consumption in certain scenarios. Conversely, CNG serves as a cleaner alternative to traditional fossil fuels, effectively lowering emissions of CO2, nitrogen oxides, and particulate matter, while its higher-octane rating contributes to improved fuel efficiency. Additionally, the integration of ethanol into natural gas-diesel dual-fuel engines has shown promising results, enhancing power performance and reducing engine knock, thereby further supporting the viability of these alternative fuels in mitigating environmental impacts. Future research on alternative fuels such as ethanol and compressed natural gas (CNG) should prioritize the development of hybrid fuel systems that integrate these fuels with renewable energy sources like solar and wind power. Additionally, integrating energy storage solutions, such as battery systems, can further improve the flexibility and cost-effectiveness of these hybrid systems, potentially reducing overall energy costs by up to 38% compared to standalone systems.

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