Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

The Impact of Alternative Fuels on the Performance and Emissions of Petrol Engines: A Review

Mohamed Hofny[1], Nouby Ghazaly[1,2,*], Ahmed Shmroukh[1,3], Mostafa Abouelsoud[1]

1 Department of Mechanical Engineering, Faculty of Engineering, South Valley University. Qena 83523, Egypt
2 Technical College, Imam Ja'afar Al-Sadiq University, Baghdad, Iraq
3 Faculty of Industry and Energy Technology, New Cairo Technological University, Cairo 11835, Egypt

ARTICLE INFO

Article history:
Received 3 June 2024
Received in revised form 15 September 2024
Accepted 23 September 2024
Available online 10 October 2024

Keywords:
SI engines; alternative fuels; HCNG; CNG; ethanol; performance and emissions

ABSTRACT

Recently, the combustion of fuel has emerged as a significant global concern. Numerous studies have highlighted the various emissions produced by different fuels. Due to the harmful pollutants and greenhouse gases emitted by fossil fuels, there has been a shift towards renewable and alternative energy sources to mitigate these adverse environmental impacts. This overview presents an in-depth analysis of current alternative fuels utilized in spark ignition (SI) engines, particularly examining the differences in performance and emissions associated with the use of hydrogen-enriched natural gas (HCNG), compressed natural gas (CNG), and ethanol as substitutes for traditional fuels. Various engine types, configurations, and operational conditions are presented to evaluate the suitability and impact of these fuels on engine performance and emission profiles. This review is intended to function as a comprehensive resource guide for future research directions, development of engine technologies, and formulation of policies related to the adoption of cleaner fuel alternatives in the internal combustion engine (ICE) sector. Biofuels show potential, but it needs to be sustainable to avoid impacting food resources as the push for greener energy continues.

1. Introduction

Transportation is another sector whereby internal combustion engines particularly those burning fossil fuels have proved devastating to the environment given the outcome they produce mostly greenhouse gases and other pollutants [1]. Therefore, there has been a rapid transition to renewable and or synthetic energy sources as a measure of reducing these effects. Most recent researches have proved that fuels like hydrogen, natural gas and alcohol may reduce the emission of carbon by a large margin without much compromising on the efficiency of engine [2]. Air pollution, resulting primarily from energy production and consumption, poses both global and local challenges and contributes significantly to climate change. Energy plays a vital role in every aspect of life, including industrial manufacturing, transportation, and electricity generation in thermal power plants. Electricity is also

---

[*] *Corresponding author.*
E-mail address: nouby.ghazaly@eng.svu.edu.eg

https://doi.org/10.37934/arfmts.122.1.118162

recognized as a key factor in virtually all human endeavours. The rapid increase in the global population is closely linked to increased energy use and growing environmental issues. This situation necessitates the adoption of innovative methods to reduce emissions from power plants [3-5]. The ongoing use and consumption of fossil-based fuels in ICEs are leading to the exhaustion of limited fuel reserves, the release of harmful gases, the pollution of land and water bodies, climate change, and irreversible damage to the environment. At the current rate of use, British Petroleum has indicated that oil and gas reserves might be depleted over the course of the next five decades, while coal could run out in approximately 115 years [6-8]. As worldwide attention on protecting the atmosphere has increased, efforts to reduce automobile exhaust emissions are growing. Exploring alternative fuels and clean energy represents a promising approach for enhancing engine performance while decreasing the reliance on oil [9-12]. In the future, it is essential to adopt alternative fuels that nearly match the efficiency of current fuels to mitigate environmental pollution and greenhouse gas emissions by replacing high-carbon content fossil fuels. Although fuels derived from renewable sources may not satisfy our imminent energy demands, the emphasis is on enhancing engine efficiency and minimizing emissions. There is potential for innovation in engines that employ a combination of primary and alternative fuels through "dual fuelling" strategies to improve performance, thereby addressing the disproportionate use of gasoline [13,14].

The Energy Policy Act (EPAct) identifies a wide range of non-traditional fuels as alternative options. These include alcohols such as ethanol (specifically when blended with more than 85% gasoline), natural gas (NG) and its domestically produced liquefied forms, liquefied petroleum gas (LPG), liquid fuels derived from coal, hydrogen (H_2), pure biodiesel (B100), and fuels made from biological materials other than alcohol. Additionally, it encompasses any fuel with a minimal petroleum base that provides significant benefits in terms of energy security and environmental improvement [15-17]. Alternative fuels produce different emissions; for example, NG produces reduced emissions of hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM), albeit with an increase in nitrogen oxide (NOx) emissions [18,19]. It stands out as an optimal alternative fuel due to its minimal carbon content. Owing to the adaptability of the injection system in a positive ignition engine, port fuel injection is the preferred method in NG engines instead of direct injection [20]. Alcohol-based fuels, especially ethanol and methanol, have become significant alternatives for eco-friendly transportation and energy production because they generally emit less carbon dioxide (CO_2). Their higher-octane number (ON) makes them a good fit for SI engines, and they can also be used in lower blend ratios for compression ignition (CI) engines. There has already been considerable research and development on the use of alcohol fuels in SI engines because they produce low HC and CO emissions [21-23]. Biodiesel is combusted with diesel by various blends, which results in high NOx but low HC, CO, and PM emissions [24]. In recent years, the utilization of alternative fuels has increased in different countries, as shown in Figure 1 [25]. Due to the pollutants (NOx and PM) that diesel engines release, the use of gasoline fuel in passenger automobiles has once again become popular. Furthermore, research and development on the use of alternative and environmentally friendly fuels in passenger cars has been ongoing [26,27]. These types of fuels have gained attention owing to the scarcity of fossil fuels, environmental pollution, and increasing cost [28,29]. Alternative fuels are known as oxygenated biofuels; thus, they reduce exhaust emissions and dependence on fossil fuels [30]. Recently, alternative fuels have been blended with fossil fuels to increase the percentage use of alternative fuels with respect to fossil fuels [31-33].

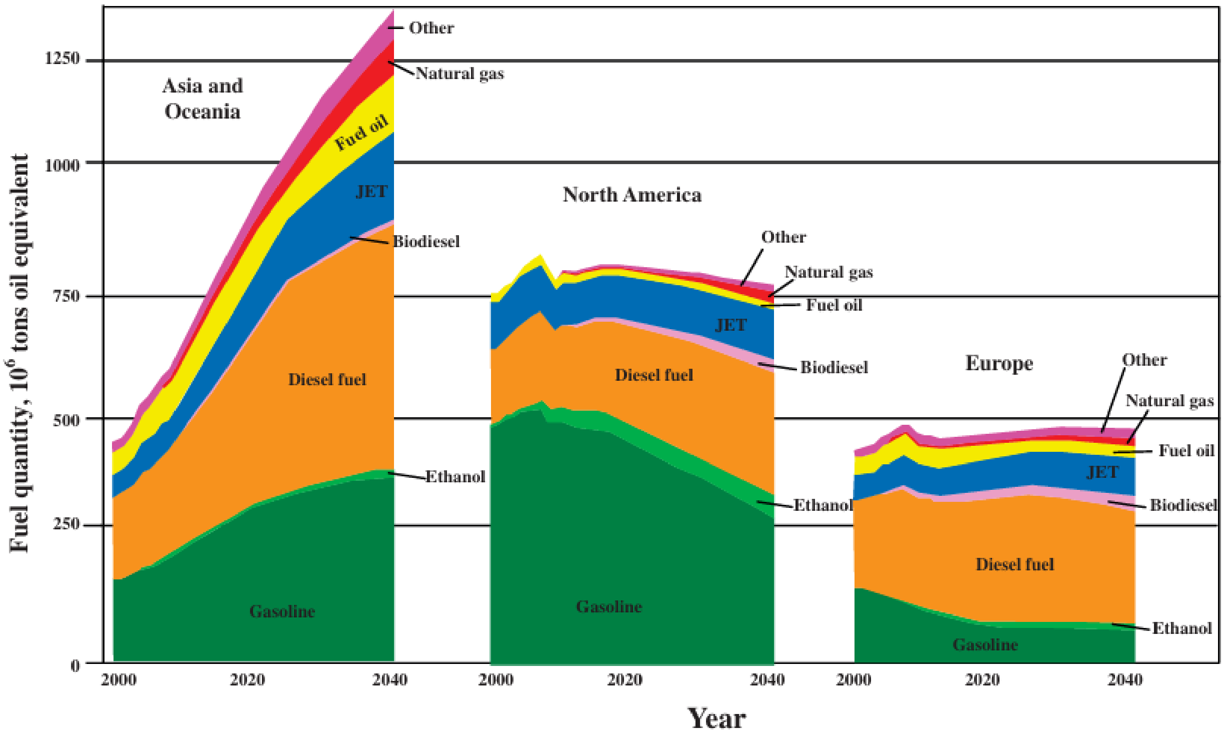

Fig. 1. Global fuel consumption of energy [25]

A wide array of research has been undertaken to highlight the role of using alternative fuels in SI engines. Liang [34] discussed the physical and chemical properties of compressed natural gas (CNG) and the two modes of combustion (homogeneous premixed combustion and heterogeneous diffusion combustion) in ICEs. Furthermore, the impact of CNG on the performance of int was compared with that of gasoline engines. Duan *et al.,* [35] aimed to enhance the combustion efficiency and reduce emissions in SI engines operating under conditions of lean combustion. This paper explores a dual-injection strategy that combines gasoline port injection (GPI) with natural gas direct injection (NDI). Kar *et al.,* [36] carried out experiments on a 4-cylinder engine that was downsized and turbocharged, operated with SI and fuelled by either CNG through DI or GIs. Three distinct approaches for preparing fuel-air mixtures have been explored: running the engine at a stoichiometric ratio without adding external diluents, utilizing stoichiometric ratios while incorporating external exhaust gas recirculation (EGR), and implementing a lean burn strategy. Chen *et al.,* [37] investigated the combustion properties and performance of a dual-fuel engine using a mixture of NG with methanol and with gasoline. Masum *et al.,* [38] compared exhaust emissions from an SI engine using blends of ethanol-gasoline and methanol-gasoline to evaluate the effects of these blends compared to those of pure gasoline on the combustion process and the air-fuel equivalence ratio. Eyidogan *et al.,* [39] indicated that engines fuelled with ethanol-gasoline (E5, E10) and methanol-gasoline (M5, M10) blends exhibited higher BSFFs than those fuelled with pure gasoline. Masum *et al.,* [40] investigated the impact of multialcohol gasoline blends by optimizing fuel properties and comparing them to traditional ethanol blends such as E10/E15. Geo *et al.,* [41] investigated the impact of blending different alcohols with gasoline on a commercial gasoline engine's performance. They compared benzyl alcohol (higher order) and ethanol (lower order) blends with gasoline, examining BTE, EGT, emission parameters, cylinder pressure, and the rate of heat release. Yusoff *et al.,* [42] used a 1.6 L four-cylinder CamPro engine from PROTON Malaysia with different blends of ethanol and isobutanol with gasoline to study engine performance and exhaust emissions. Elfasakhany and Mahrous [43] reported that the addition of small amounts of n-butanol and methanol to pure gasoline negatively impacts engine performance and exhaust gas emissions. Yusoff *et al.,* [44] explored the impact of butanol isomers (n-butanol, sec-butanol, tert-butanol, and isobutanol) blended with gasoline at a 20% volume on a four-cylinder SI engine's performance and emissions.

In this review, we will examine natural gas, hydrogen, and ethanol fuels based on various performance and emission parameters, including brake power (BP), brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), and HC, CO_2, CO, and NOx emissions. These parameters will provide the best insights into engine performance and emissions. However, there is a notable absence of a thorough review that summarizes and assesses the various alternatives along with their benefits and limitations, as well as their potential for broader adoption. Furthermore, alternative fuels are frequently evaluated in a competitive manner, suggesting the use of a single fuel for all applications.

2. Natural Gas in SI engines

Natural gas is a naturally occurring blend of hydrocarbon and nonhydrocarbon gases and is present in porous formations deep within the earth mixed with hydrocarbon gases. It serves as a substitute for traditional fuel in IC engines because it is clean, inexpensive, and more efficient than other alternative fuels. It can be used in IC engines in the form of liquefied natural gas (CNG) and liquefied natural gas (LNG). Compressed natural gas is used extensively due to its low cost and easy storage. Natural gas hydrates (NGHs), which are widely found in seafloor and permafrost zones, are viewed as potential replacements for fossil fuels that could eventually run out due to steadily rising energy demand. There are different NG hydrate resources, such as the distribution of gas hydrates, geologic characterization of gas hydrates, and categorization of gas hydrate deposit NGHs [45]. This fuel is used in IC engines because it is considered the cleanest fossil fuel for both CI and SI engines. This fuel has a relatively lower cost than fossil fuels [46,47]. It has low emissions compared to other fuels, as it has a high hydrogen-to-carbon ratio due to its high composition of methane, which is considered a renewable fuel because it is not only found in NG but is also produced from biomass. The properties of natural gas and gasoline are compared in Table 1 [48,49].

Compared with conventional fuels, natural gas has a higher ON (120:130), which is considered a good antiknock property and produces less CO_2 emissions [50,51]. In general, it reduces carbon emissions [52]. It produces no sulphur or SO_X emissions and produces approximately no particulate matter [53], but engines fuelled with NG have lower power and thermal efficiency than gasoline fuel [54,55]. Additionally, they are affected by knocking on the stratified combustion process for high-pressure states [56]. According to the CFD analysis of spark ignition engines fuelled with NG at different compression ratios (CRs), 14:1 is the best ratio because it results in the lowest specific fuel consumption and CO and NOx emissions and provides the highest indicated power and indicated thermal efficiency, as shown in Figure 2 [57]. An increase in the prechamber area is proven to improve the ignition energy in the cylinder and cause complete combustion but late ignition timing. A suitable size of this chamber optimizes the ignition energy and ignition timing [53]. According to the energy and exergy efficiencies, NG has been proven to be better than gasoline due to its high CR, as NG has a high ON [58]. The BTE of the heavy-duty spark ignition engine increased as the CR increased, whereas the BSFC decreased as the CR increased. Furthermore, when the CR increased, the increase in the BTE and BSFC gradually decreased [59]. Due to the suitability of injection systems for positive ignition engines, port fuel injection (PFI) rather than direct injection is frequently used in NG engines. Nevertheless, methane, which has a 28-fold greater global warming potential than CO_2, is quite likely to be emitted during valve overlap in PFI engines. The methane slip problem could be mitigated by adjusting the timing of the intake and exhaust valves. However, few studies have investigated how valve timing variations affect engine performance and emissions in NG engines.

Table 1
Properties of natural gas versus gasoline [49]

Parameter	The Units	Gasoline (G)	Natural Gas (NG)
Density	kg/m³	740 *	-0.74 **
Octane number		95	-120
Lower heating value (LHV)	MJ/kg	-44.0	-47.5
Stoichiometric mixture (A/F)	|kg/kg	~14.7/1 ***	~17.2/1 ***
Boiling temperature	°C	25-215 ***	-162 ***
Specific heat of vaporization	kJ/kg	~380	~550
Freezing point	°C	-40 ***	-162 ***
Autoignition temperature	°C	~400	~540
Adiabatic flame temperature	°C	~2150	~1890
Flame spread rate	m/s	~0.5	~0.41
H/C ratio		~0.163	~0.316
Chemical element/component	% (mass)	Carbon: ~86.35 Hydrogen: ~0.139 Oxygen: ~0.025	Methane: 91.97 Ethane: 5.75 Propane: 1.30 Butane: 0.281 Nitrogen: 0.562 Carbon dioxide: 0.0

* At 20 °C. ** at 0 °C and 101.3 kPa pressure. *** at 101.3 kPa pressure

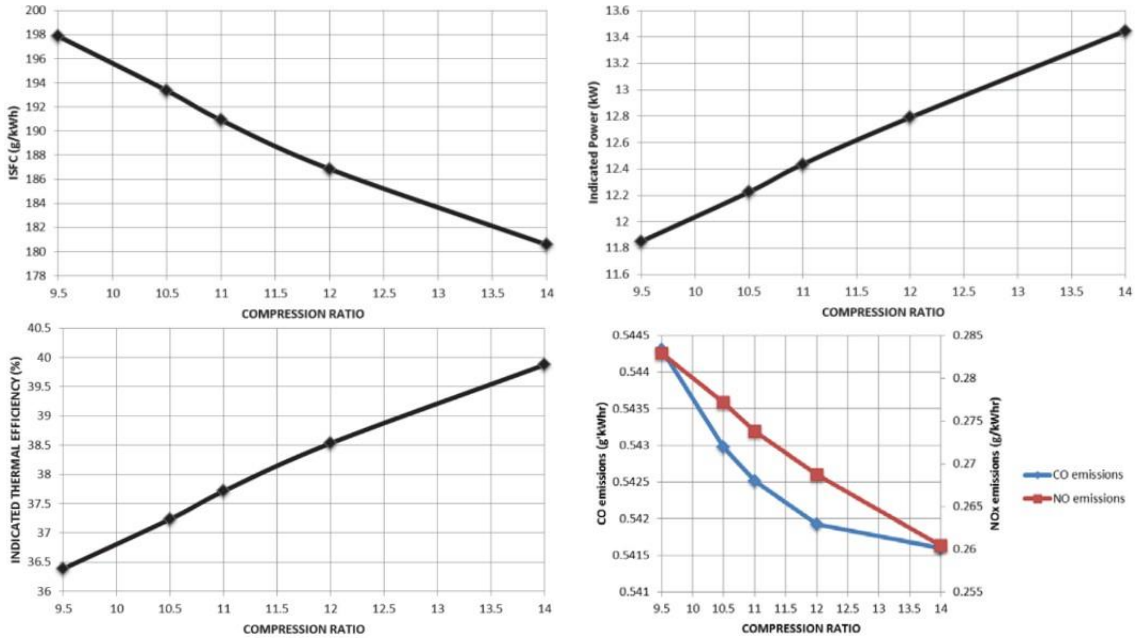

Fig. 2. Natural gas specifications at various CRs [57]

2.1 Compressed Natural Gas (CNG) in SI Engines

Compared to gasoline fuel, CNG has high efficiency, low emissions, and low specific fuel consumption in both PFE and DI systems. However, the combustion characteristics of DI-CNG are better than those of PFE-CNG [60,61]. Compared with liquid fuel (gasoline), CNG has insufficient power generated for an engine of the same capacity [62,63]. Compressed natural gas (CNG) was found to have a greater energy output in relation to the engine load than did gasoline. Compared to gasoline, the longer combustion time and higher combustion temperature of CNG result in greater energy losses due to wall heat transfer and exhaust gases. As a result, CNG has a greater energy portion that matches the exhaust gas and wall heat transfer. By decreasing the energy destruction caused by wall heat transfer, exhaust losses, and unaccounted losses, CNG can perform more efficiently than gasoline [62,64], and the properties of CNG are shown in Table 2 compared to those of hydrous ethanol [65]. Some of the previous authors have performed experiments and research that has proven the benefits of using natural gas in spark Ignition (SI) Engines. When comparing the combustion of CNG and gasoline in direct injection SI engines, CNG produced lower CO2 emissions (16%:19% lower than gasoline), higher efficiency at high loads, and the same efficiency at partial loads [66]. When using a PFI system with either CNG or gasoline, CNG decreases brake power (BP) by 19%; CO2, NOx, CO, and HC emissions by 50%, 20%, 90%, and 96%, respectively; and brake specific energy consumption (BSEC) by 14% [67]. DI CNG provides better scavenging than does PFI CNG [68]. A direct injection (DI) system has been shown to provide high brake power for a four-cylinder, four-stroke cycle using CNG at different speeds (8-9% higher than that of PI) [69]. Brake power is affected by ignition timing, as it has been shown that an advance in ignition timing increases brake power [70]. Gasoline 97 has high brake power (28.8% increase) compared to CNG [71]. The specific fuel consumption (SFC) of CNG is lower than that of gasoline under light loads [72]. The BSFC demonstrates an improvement in fuel consumption at 7% CNG whenever the engine reaches its maximum power at various speeds. Throughout the speed range, the thermal efficiency of CNG is consistently greater than that of gasoline. At 4000 and 5000 rpm, the maximum BTE was found to be 25.5% for gasoline and 29% for CNG [73]. Three different types of piston bowls with two CRs (11.5:1 and 12.5:1) were studied. PS1 and PS2 are concentric bowls, and PS3 is an eccentric bowl. At full loads, PS1 provided the best BSFC at a CR of 11.5:1 [74]. After using different equivalence ratios, CNG has a lower BSFC than gasoline when the equivalence ratio is 0.7–1.2, but the BSFC starts to increase when the equivalence ratio is 1.3–1.4. The brake thermal efficiency depends on the equivalence ratio. The BTE of all fuels increases with increasing equivalence ratio until approximately the stoichiometric point and then slightly decreases. The average BTE differences between CNG and G9C1 and between CNG and gasoline are 10.2% and 3.5%, respectively [75]. A high CR causes knocking when using gasoline fuel, while CNG causes no knocking because it has a high ON. An increase in the CR increases the ITE (indicated thermal efficiency), flame development speed, and ISCO2 emission but decreases the FDA (flame development angle) and CD (combustion duration) ISCO and ISHC emissions. The FDA and CD of gasoline fuel at 12 CR can be obtained by 16 CR-CNG [76]. An increase in the CR increases the total FC with increasing BP [77]. The BTE of CNG is greater than that of gasoline [78,79].

In comparison to (G)92, CNG had reduced exhaust emission contents of HC (52.36%), CO (44.68%), and NOx (25.43%) [80]. It has been found that CNG has a lower brake mean effective pressure than BMEP and BSFC and has a higher efficiency and reduced emissions of CO, CO_2, and HC, although it produces more NOx than gasoline does [81]. This study evaluated the effect of using CNG with different caloric values on engine parameters, aiming to assess how various compositions of NG influence the engine's full-load performance and emission characteristics in compliance with emission standards [82]. When using CNG in a turbocharged SI engine, CNG enhances the TE and reduces CO_2 emissions despite lower load capacities due to its PI system. However, it increases NOx emissions. A higher ON of CNG allows for improved combustion efficiency and advanced spark timing, making it a viable alternative to gasoline [83]. A study comparing engine performance and exhaust emissions between gasoline and CNG in a retrofitted IS car engine revealed that CNG reduced BP and SFC but increased BTE and EGT, especially at higher throttle positions. Despite higher NOx emissions, CNG significantly lowered other harmful emissions (HC, CO, O_2, and CO_2) compared to gasoline [84]. A study demonstrated that a new SI engine design incorporating a passive prechamber ignition concept, high CR, and Miller cycle not only improves the indicated efficiency by approximately 3% under high load/speed conditions but also significantly reduces fuel consumption by 15% and CO2 emissions by 25% in simulated driving cycles compared to those of conventional gasoline engines [85]. An experimental study on an SI engine fuelled with CNG, comparing standard gasoline, commercial, and novel CNG conversion kits, showed that the novel kit matched the low throttle power and exceeded the high throttle power of the commercial kit, with lower CO and HC emissions at higher loads [86]. A study investigated how the NG composition affects CNG engine combustion and emissions, highlighting the impact on the engine power, T, BMEP, and BSFC under full load conditions. It proposes a correlation between MN and engine power, offering a method to estimate power variations with different NG [87]. Studying the performance of a dual-fuel IC engine running on CNG and gasoline indicated that CNG offers higher exergy efficiency at all engine speeds, despite lower power and T due to VE drop. This highlights that while CNG reduces SFC, gasoline's higher volumetric energy density and ease of storage are significant advantages [88]. The previous studies of CNG are provided in Table 3.

2.2 Hydrogen-enriched Compressed Natural Gas HCNG

Hydrogen is seen as a promising future fuel for internal combustion engines because of its lack of carbon emissions. However, there are significant hurdles to overcome before hydrogen can reach mainstream levels in the transport sector. Currently, the shortage of hydrogen infrastructure and refueling options is slowing the rollout of hydrogen-fuelled vehicles. One interesting workaround is blending hydrogen with CNG, which takes advantage of hydrogen's unique qualities while lessening the immediate need for pure hydrogen. This approach is compatible with the existing NG infrastructure [89,90]. Hydrogen is a high-efficiency alternative fuel with outstanding qualities. The entrance of hydrogen-powered vehicles into the transportation industry is expected to reduce fuel consumption and air pollution caused by exhaust emissions [91,92]. Hydrogen (H2), which is the lightest gas, possesses excellent combustion characteristics, including broad flammability ranges, minimal ignition energy requirements, rapid flame propagation, and virtually zero emissions [93,94]. Hydrogen can be blended with CNG in small volume or energy percentages to enhance combustion characteristics and yield considerable improvements in engine performance and emission reductions. Consequently, numerous studies have introduced hydrogen into NG in acceptable proportions by volume, ranging from 2% to 50%, for use in IC engines.

Table 2
Properties of CNG [65]

Property	Hydrous ethanol (E100)	Compressed Natural gas (CNG)
Composition (%vol)	C2H6O – 95.1% H2O – 4.9%	CH4 – 89% C2H6 – 6% C3H8 – 1.8% CO2 – 1.5% N2 – 0.7%/Others – 1%
Density at 1 atm and 15 °C (kg/m³)	805.2	0.71
Motor octane number	91.8	120
Research octane number	> 100	120
Auto ignition temperature (°C)	363	540
Lower heating value (LHV) (MJ/kg)	24.76	49
Stoichiometric air fuel ratio	8.36	17.08

Table 3
Previous studies on CNG

Study ID	Engine Type	Performance Improvements	Performance Declines	Fuel Consumption Changes	Emissions Reductions	Emissions Increases
Li *et al.,* [60], Melaika *et al.,* [61]	DI-CNG, SI Engine	Highest engine efficiency, lowest SFC.	-	Lowest SFC.	Further reductions in particulates compared to GDI and PFI-CNG	-
	PFI-CNG, SI Engine	Improved engine efficiency over GDI.	-	Reduced SFC compared to GDI.	Reduced CO, CO2, HC, and NOx emissions compared to GDI.	-
	GDI, SI Engine	Shorter combustion duration.	-	Higher SFC.	-	Higher THC and CO emissions compared to CNG systems.
Tahir *et al.,* [63]	Single cylinder SI engine	Lower heat transfer rate compared to gasoline, potentially better for engine lifespan due to lower operating temperatures	18.5% lower power output compared to gasoline, 20% less cylinder pressure with CNG, 23% less heat transfer rate with CNG	-	Lower emissions due to CNG's cleaner burning properties	-
Sahoo and Srivastava [64]	Single-cylinder, four-stroke, water-cooled, spark ignition	Higher output energy, TE, exergy efficiency (26.80% at 30 Nm load compared to gasoline's 25.50%), lower unaccounted energy fraction, lower exergy destruction at all loads.	Higher engine wall heat transfers due to high combustion chamber temperature and lower burning velocity	Lower BSFC compared to gasoline.	Potentially lower emissions due to higher efficiency and combustion characteristics.	-
da Costa *et al.,* [65]	Single-cylinder, SI CNG/E100 dual-fuel	Operating in dual-fuel mode enhances fuel conversion efficiency over exclusive CNG use, thanks to improved combustion timing and reduced emissions of CO and HCs. Implementing internal EGR further boosts efficiency due to reduced pumping losses and diminished wall heat transfer.	Internal EGR deteriorates the combustion process, including aspects like ignition delay, duration of combustion, and stability, but it enhances efficiency through the reduction of pumping losses and heat transfer to the walls.	-	NOx emissions increase with dual-fuel operation but are significantly reduced (up to 70%) with iEGR. CO and HCs emissions are lower in dual-fuel mode compared to CNG-only operation.	-

Kar *et al.,* [66]	4-cylinder, downsized, boosted spark ignition	DI CNG achieved performance comparable to the baseline GDI engine under stoichiometric conditions, delivering peak torque at lower engine speeds and providing significant advantages in fuel economy. Lean burn with DI CNG demonstrated higher BTE than stoichiometric operation with external EGR.	-	DI CNG showed lower total CO2 equivalent emissions than GDI, indicating fuel economy benefits.	DI CNG operation consistently resulted in lower total CO2 equivalent emissions compared to Gasoline Direct Injection (GDI) across a range of operating conditions.	NOx emissions rise when operating on dual-fuel compared to using CNG alone. Top of Form
Duc *et al.,* [67]	Single-cylinder, PFI, SI engine.	-	19% decrease in BP, 14% increase in BSEC	-	CO2 emissions are reduced by up to 50%, NOx emissions see a decrease of 20%, while CO and HC emissions are lowered by up to 90% and 96%, respectively.	-
Patel and Brahmbhatt [69]	Maruti Esteem's 4-cylinder, 4-stroke, water-cooled petrol engine	CNG-DI system exhibited an average 7-8% reduction in BSFC, 8-9% higher brake torque leading to higher BP, and 6-7% higher BTE compared to CNG-PI system.	-	Average 7-8% lower BSFC in CNG-DI compared to CNG-PI system.	-	-
El-Sharkawy *et al.,* [70]	G4EH Gasoline Engine (Modified for CNG)	Advancing the static ignition timing from 15° BTDC to 24° BTDC at full load led to enhancements BP by 4.07%, brake torque by 4.67%, BTE by 3.58%, and HC emissions reduction by 4.89%. Top of Form	-	Advancing static ignition timing reduced BSFC, indicating improved fuel efficiency.	A slight reduction in CO2 emissions was noted.	Advancing static ignition timing increased HC due to more fuel-air mixture being pushed into crevices volumes.

Usman and Hayat [71]	Single cylinder, 4-stroke, SI, water cooled	-	G97 showed 28.8% increase in BP compared to CNG	CNG exhibited a 17.2% decrease in BSFC compared to G97	CNG had lower emission contents compared to G97: 59.7% lower HC, 43.6% lower CO, 19% lower CO2, and 20.1% lower NOx emissions	-
Yontar and Doğu [72]	Honda L13A4 i-DSI (Dual Sequential Ignition Engine)	-	Utilizing CNG results in a decrease across all engine performance metrics, including torque, power, VE, and SFC, compared to gasoline.	SFC increases with CNG	Reductions in CO2 and HC emissions with CNG	NOx emissions remain a concern with CNG, though specific results for increases or decreases are tied to operational conditions (not detailed in the excerpt)
Nor Hisham *et al.,* [73]	Renault F3R Engine	-	CNG reduced BP and BMEP by approximately 16%.	CNG shows improvement in SFC by approximately 7% when achieving peak power.	-	-
Le *et al.,* [74]	Single cylinder diesel engine converted to PI CNG engine	Employing a concentric bowl-in-piston design with a CR of 11.5:1 led to the lowest BSFC and the highest BP.	-	Significant impact of piston-top shape and CR on combustion efficiency, with an optimal combination found for high combustion efficiency.	-	-
Yontar and Doğu [75]	Honda L13A4 i-DSI (Dual Sequential Ignition Engine)	-	-	-	CNG and Gasoline-CNG mixture reduce CO2, CO, HC emissions except for NOx, where CNG has the highest NOx emissions	NOx emissions were higher for CNG compared to gasoline and Gasoline-CNG mixture

Sahoo and Srivastava [76]	Single-cylinder, four-stroke, PFI, SI engine	At higher CR (up to 16 for CNG), improved TE were observed for CNG compared to gasoline.	Knock intensity was high at CR 12 and 7 bar IMEP for gasoline, limiting maximum CR for gasoline to 12 due to knock. No knock observed for CNG even at CR 16.	CNG showed improved FC and TE at higher CR compared to gasoline.	Under full load operating conditions, a CNG engine emits 15-30% less CO and 10-13% less CO2 compared to a gasoline engine. Top of Form	-
Gowtham *et al.,* [77]	Two-Stroke SI Engine (Yamaha RX100)	Increased fuel efficiency and output at higher CRs under half load conditions. High torque achieved at lower CRs due to increased pulling capacity of the engine.	-	Total fuel consumption increased with capacity at the least CRs but decreased with an increase in CR due to improved combustion efficiency.	CO and HC emissions are reduced due to more complete combustion achieved at CRs.	NOx emissions increase due to higher BTE at high CRs, but specific CO emissions are reduced due to lower fuel efficiency at lower CR%.
Usman *et al.,* [80]	Single-cylinder, four-stroke, SI engine.	-	Gasoline (G)92 showed a 39.93% increase in BP compared to CNG.	CNG exhibited a reduction in BSEC by 7.94% compared to Gasoline (G)92. Top of Form	CNG led to significant reductions in HC (52.36%), CO (44.68%), NOx (25.43%), and CO2 emissions compared to Gasoline (G)92.	-
Aslam *et al.,* [81]	1.5 L 4-cylinder Proton Magma SI car engine	Higher efficiency and lower emissions of CO, CO2, HC with CNG.	Low BMEP and BSFC with CNG.	CNG shows higher efficiency and lower BSFC compared to gasoline.	Significant reductions in CO, CO2, HC emissions with CNG.	More NOx emissions with CNG compared to gasoline.
Park *et al.,* [82]	11 L Inline Six-Cylinder NG Engine. (CNG with different caloric values)	Torque increases proportionally with the caloric value of CNG.	Torque increases proportionally with the caloric value of CNG.	FC is inversely proportional to the caloric value, with lower caloric value gases requiring more fuel to maintain performance.	-	Using gas with a lower caloric value than the reference fuel slightly increases CO emissions and significantly increases NOx emissions. However, after adaptive learning calibration, NOx emissions are reduced

						below the emission limit.
Lee *et al.,* [83]	11 L Inline Six-Cylinder NG Engine	Enhanced TE under maximum load conditions was achieved by advancing the spark timing, attributable to the higher ON of CNG.	Maximum loads were found to be 4-23% lower than those of GDI engines, a consequence of utilizing a PI system. Top of Form	FC is inversely proportional to the caloric value, with lower caloric value gases requiring more fuel to maintain performance.	Engine-out NOx emissions from CNG PFI combustion were higher compared to GDI combustion. However, lower CO2 emissions with higher combustion efficiency were attainable. Top of Form	Using gas with a lower caloric value than the reference fuel slightly increases CO emissions and significantly increases NOx emissions, which can be reduced below the emission limit after adaptive learning calibration.
Jahirul *et al.,* [84]	1.6 L 4-cylinder petrol engine retrofitted to CNG	1.6% higher BTE with CNG at 80% throttle, 24.21% higher EGT indicating more complete combustion.	There was a 19.25% reduction in BP with CNG at a 50% throttle position and a 10.86% reduction at an 80% throttle position, respectively.	When fueled with CNG, there was a 15.96% reduction in BSFC at a 50% throttle position and a 14.68% reduction at an 80% throttle position, respectively.	Significant reductions in HC, CO, and CO2 emissions with CNG	Over the speed range of 1500–5500 rpm at 80% throttle, CNG usage resulted in an average of 40.84% higher NOx emissions compared to gasoline.
Payri *et al.,* [85]	SI Engine with passive prechamber	3% increase in indicated efficiency at high load/speed conditions, improved performance with EGR at low-end torque region	-	15% reduction in fuel consumption during WLTP driving-cycle simulations	25% reduction in CO2 emissions during WLTP driving-cycle simulations	-
Putrasari *et al.,* [86]	Honda L15A four cylinders 1497 cm3 SI engine	Maximum BP improved with proposed CNG conversion kit at higher throttle positions.	-	-	CO and HC emissions lower at 80% throttle position compared to 25% for both commercially and proposed CNG conversion kits.	-
Kakaee and Karimi [87]	1.65 L 4-cylinder EF7 CNG Engine	Increased BMEP, BTE, power, and torque with higher Methane Number	-	Best BSFC observed for Gas A, with BSFC increasing	-	-

		(MN). A linear equation was proposed to predict the change in power as a function of MN, indicating a direct relationship between MN and engine power.		significantly for fuels with higher MN at engine speeds over 3000 RPM.		
Ameri *et al.,* [88]	Four-cylinder, four-stroke Iran Khodro XU7 JPL3 1.8 L SI engine	CNG-fuel showed higher exergy efficiency than gasoline at all engine speeds.	Power and torque of the CNG-fuel engine are lower than for the gasoline-fuel engine due to VE drop.	SFC of the CNG-fuel engine is lower than for the gasoline-fuel engine.	-	-

The reduced emissions from vehicles fuelled by HCNG could assist in adhering to strict emission standards [95,96]. Hydrogen is renewable, and the quantity of energy required to produce it is minimal. In terms of direct injection, hydrogen engines exceed gasoline engines by approximately 30%. Because hydrogen has a greater ON than gasoline, it can run at a higher CR. Compared to the breaking power, the thermal efficiency of hydrogen has demonstrated its commendable performance. Furthermore, harmful chemical emissions are lower for hydrogen than for gasoline [14]. Compared to CNG, hydrogen significantly enhances brake power and reduces CO and HC emissions to zero, positioning it as the most effective fuel for reducing carbon-based emissions, despite a slight increase in NOx emissions [97,98].

Hence, the studies done on hydrogen-enriched Natural Gas (HCNG) blends show enhancement of performance and reduction of emissions. Therefore, converting to HCNG blends (15% and 25% H_2 by volume) led to a 15–20% improvement in BTE. 7% at low load and 19% at high load respectively, as translated into average AWCs. 4% at high load. Furthermore, HCNG blends decreased the CO and HC emission by a staggering 50% and 90% respectively, while SOx emissions only increased by a marginal level because of the higher combustion temperatures [99]. A study evaluated the performance and emissions of a commercially available CNG vehicle retrofitted with a sequential injection kit using gasoline, CNG, and hydrogen-blended CNG (HCNG 10% and HCNG 18%) as fuels in a Spark Ignited (SI) MPFI engine. The results show that HCNG blends improve torque and power by up to 6% and 4%, respectively, and reduce fuel consumption and emissions of CO, HC, and CO2 compared to CNG, with an increase in NOx emissions, demonstrating the kit's suitability for HCNG blends [78]. A study examined unregulated emissions from a heavy-duty six-cylinder engine fuelled with CNG and HCNG using a transient engine dynamometer and Fourier transform infrared spectroscopy gas analyser for measurement. HCNG significantly reduces both regulated emissions (CO, NO, HC, and PM) and several unregulated emissions, although it slightly increases methanol, ethanol, formaldehyde, and acetaldehyde, suggesting that HCNG has potential as a promising fuel for the transport sector and is compatible with exhaust after-treatment devices [100]. Using five hydrogen energy share levels, a study measured the effects of hydrogen enrichment on combustion stability in a natural gas SI engine, focusing on metrics such as peak combustion pressure and combustion duration. The results showed that higher hydrogen shares significantly reduced cycle-to-cycle variability and improved combustion efficiency, with a strong correlation between peak combustion pressure and the CA50 combustion phase across all levels [101]. A laser-ignited engine prototype running on HCNG was developed to compare its performance, emissions, and combustion characteristics against those of traditional spark ignition (SI) methods. The findings revealed that using maximum brake torque (MBT) timing in laser ignition mode significantly enhanced engine efficiency, reduced emissions, and minimized cycle-to-cycle variations, especially at an optimum CA of 31° CA before the top dead centre (BTDC), demonstrating the potential of laser ignition for improving HCNG engine performance [102]. An experiment in which a diesel engine was modified to operate on CNG, H_2, and HCNG with laser ignition demonstrated notable enhancements in engine performance and emissions. Specifically, laser ignition increased the engine torque, improved the brake thermal efficiency up to 38.6% for HCNG, and reduced the fuel consumption and exhaust gas temperature. Additionally, it led to lower CO and NOx emissions, particularly with hydrogen-enriched fuel, underscoring the effectiveness of laser ignition in improving both efficiency and environmental impact [103].

A CFD simulation was conducted to evaluate the impact of hydrogen enrichment on combustion and emissions in a large-bore medium-speed NG engine using prechamber-initiated turbulent jet ignition. The results indicate that increasing hydrogen levels up to 30% enhances combustion efficiency and reduces emissions of CO, total HCs, and nonmethane hydrocarbons, while NOx emissions increase [104]. A study investigated the laser ignition of HCNG for improving ICE performance and emissions using a Q-switched Nd:YAG laser. The findings revealed that hydrogen enrichment expands the lean-burn limit and accelerates flame kernel development, leading to an advanced start of combustion and reduced combustion duration, thereby enhancing lean-burn combustion capabilities and efficiency in spark ignition engines [105]. This study investigated the impact of the excess air ratio and ignition advance angle on the combustion and emission characteristics of HCNG in a 6-cylinder CNG engine with blends of 0%, 20%, and 40% hydrogen. The results indicate that hydrogen blending enhances combustion stability and reduces CO and CH4 emissions [106]. A study explored the impact of direct injection of hydrogen on the lean combustion efficiency of natural gas IC engines using a dual-fuel optical engine with high compression. The results demonstrate that hydrogen significantly enhances combustion stability and power output, with late injection timings boosting thermal efficiency due to faster flame propagation and improved combustion phasing. This study highlights how increased volumetric efficiency and in-cylinder turbulence at different hydrogen injection timings optimize combustion, offering valuable insights for enhancing NG engine performance under lean conditions [107]. A study examined the impact of two-step fuel injection in a modified four-cylinder engine using HCNG, with initial CNG injection into the air manifold followed by direct cylinder injection of HCNG. Using AVL software for analysis, the results showed that a 30% HCNG blend increases brake power, thermal efficiency, and in-cylinder pressure by up to 13.64%, reduces specific fuel consumption by up to 18%, and lowers CO and HC by up to 14% but increases NOx emissions due to higher exhaust gas temperatures [108]. A port-fuel-injection (PFI) SI engine was tested using HCNG mixtures in both SI and LI modes, demonstrating improved performance over that of the baseline CNG. Hydrogen enrichment significantly increased the in-cylinder peak pressure, rate of pressure rise, and heat release rate, with the LI mode achieving a maximum brake thermal efficiency of ~42.8% for 30HCNG and lower HC emissions than the SI mode. Additionally, BSNOx emissions were lower for HCNG than for CNG, demonstrating the potential of HCNG and laser ignition for enhancing engine efficiency and reducing emissions [109].

Through a virtual model of an 11-L CNG engine adapted for HCNG use and a parametric study using the Latin hypercube sampling method, this study assessed the impact of hydrogen addition (6–10%) on engine performance and emissions at different speeds (1000, 1300, and 1500 rpm) under full load. The results indicate that hydrogen-enriched HCNG engines can achieve torque and BSFC comparable to those of traditional methane engines, with NOx emissions similar to those of base engines at mid-range speeds, underscoring the potential of hydrogen for enhancing engine efficiency and reducing emissions [110]. Using experimental and AVL Boost simulation analyses on a Renault HR09DET engine fuelled by gasoline, CNG, and hydrogen-enriched CNG, the study revealed that hydrogen enrichment significantly lowered HC and CO emissions by up to 65% and 55%, respectively, with a slight 15% reduction in NOx emissions compared to gasoline. This further indicates that the engine's efficiency could be improved by increasing the CR, capitalizing on the higher ONs of CNG and hydrogen without reaching the knock limit [111]. A 1D simulation model of an HCNG SI engine was developed, validated with experimental data, and used to compare four EGR systems (low-pressure LP, high-pressure HP, combined HP-LP, and internal EGR) in terms of combustion, performance, and emissions. The study revealed that HP EGR yielded the lowest NOx emissions, while a combination of 10% HP and 5% LP EGR achieved the highest thermal efficiency. Internal EGR effectiveness was linked to exhaust valve timing and influenced by intake and exhaust system waves, affecting gas exchange and volumetric efficiency [112]. Chinese research on HCNG engines shows that hydrogen enrichment enhances combustion efficiency and reduces emissions, including THC, CO, and CH4, despite the potential increase in NOx emissions. Optimizing ignition timing and air-fuel ratios can maintain high thermal efficiency with regulated NOx levels, highlighting HCNG's potential for improving environmental performance and its successful application in city buses [113]. An experimental study on a single-cylinder HCNG engine demonstrated that hydrogen-enriched CNG outperforms conventional CNG by increasing power, torque, and combustion stability while reducing emissions. Specifically, hydrogen addition enhances BTE, lowers fuel consumption, and improves combustion parameters, with a 30% HCNG blend showing the best performance and emission benefits, highlighting HCNG's potential as an effective alternative to conventional automotive fuels [114]. An experimental study on a marine NG engine explored the ability of the REGR technique to enhance lean burn combustion and meet strict maritime emission regulations. By adding a hydrogen-rich reformate to the engine, a study revealed that as lean-burn limits increase, combustion efficiency improves, and NOx emissions initially increase and then decrease with increasing reformate addition, suggesting that REGR has the potential to balance NOx emissions with fuel efficiency under International Maritime Organization Tier III standards [115]. The Volkswagen Polo 1.4 was adapted for hydrogen fuel through modifications to its inlet manifold, gas injectors, oil radiator, and electronic management unit, achieving optimal operation with lean air-hydrogen mixes and low NOx emissions. The hydrogen engine demonstrated superior brake thermal efficiency over its gasoline version, except in very lean or high-speed conditions, with a best brake torque of 63 Nm at 3800 rpm and a maximum power of 32 kW at 5000 rpm, indicating its capability for urban and moderately inclined driving [116]. A study evaluated the impact of CNG-H2 on the performance and emissions of an SI engine at constant speed and varied air–fuel ratios. While adding hydrogen increases brake specific energy consumption, particularly in lean mixtures, it substantially reduces emissions such as CO and HC, highlighting CNG-H2’s potential for cleaner engine operation [117].

A study evaluated the efficacy of using HCNG in conventional CNG vehicles utilizing a commercially available CNG carburation kit for testing on an SI MPFI engine across various fuels, including gasoline, CNG, and HCNG blends (10% and 18%). The results indicated that compared with CNG, HCNG blends significantly enhance engine torque (up to 6%) and power (up to 4%) while reducing fuel consumption and emissions of CO, HC, and CO_2, albeit with a noted increase in NOx emissions, thereby demonstrating the compatibility and benefits of HCNG in improving engine performance and emissions [78]. A study conducted experiments on a turbocharged SI engine using various HCNG mixtures, adjusting excess air ratios, ignition timings, and manifold absolute pressures, with a constant engine speed of 1600 rpm. These experiments aimed to gather data on how HCNG blends affect engine torque and BSFC, as well as emissions such as NOx, CO, THC, and CH4, revealing that torque decreases while BSFC and emissions vary with changes in the engine's operating conditions [118]. The emissions from HCNG mixtures in a single-cylinder SI engine were evaluated and compared to baseline CNG emissions. The results indicate that HCNG significantly lowers CO_2, HC, and CO emissions, albeit with increased NOx emissions. The 30% HCNG blend showed the lowest knock intensity, highlighting HCNG’s potential to improve emissions and reduce knock in IC engines while decreasing greenhouse gas emissions by reducing fuel carbon intensity [48]. In a comparative study on a dual-fuel SI engine using gasoline and hydrogen, it was found that hydrogen addition, especially in a stratified manner, significantly improved brake thermal efficiency, particularly under lean conditions, by stabilizing ignition and accelerating combustion. However, while stratified hydrogen injection reduces CO and increases NOX and HC emissions due to higher combustion temperatures and varied hydrogen concentrations near the ignition source, it considerably improves the combustion efficiency and emission profile over homogeneous hydrogen distribution [119]. Testing HCNG blends in an SI engine revealed that increasing the hydrogen percentage significantly reduced the CO, CO_2, and HC emissions while enhancing the BTE without notably reducing the indicated TE or NOx at the maximum brake torque ignition timing. This suggests that costly retrofitting for variable spark timing may be unnecessary for improving performance and emissions in on-road vehicles using HCNG blends [120]. The previous studies of HCNG are provided in Table 4.

3. Ethanol Fuel in SI Engines

Alcohol-based fuels such as ethanol and methanol have beneficial properties for SI engines, including resistance to knocking, a high oxygen content that promotes clean combustion, a high temperature required for autoignition, a low freezing point, and substantial latent heat during vaporization. These previously mentioned properties play an important role in enhancing combustion efficiency, improving overall engine performance, and reducing emissions [121]. Additionally, alcohol fuels can directly reduce emissions from different engine types, such as SI, CI, and homogeneous charge compression ignition (HCCI) engines [122]. Alcohol fuels, including methanol, ethanol, butanol, and pentanol, have various advantages in IC engines. The addition of these fuels to primary fuel has been extensively studied [123]. These fuels have been found to achieve the highest performance while producing minimal exhaust emissions [124]. Alcohol fuels have a high enthalpy of vaporization and ONs. This means that using dual injection systems for alcohol and gasoline can enhance engine knocking, combustion efficiency, and engine performance [125]. The high enthalpy of alcohols not only results in reduced NOx emissions but also contributes to lowering HC, CO, and CO_2 emissions. Furthermore, it enhances engine torque and improves BSFC [126,127]. Moreover, the use of alcohol-blended fuels in small gasoline engines has been observed to impact combustion characteristics, resulting in decreased emissions and enhanced thermal efficiency [128].

Ethanol is a biofuel that can be produced from various materials, such as corn or sugarcane, as shown in Figure 3. The production of bioethanol from biomass is one method for reducing crude oil consumption and environmental pollution. Bioethanol is suitable for mixed fuel in gasoline engines due to its high NOx however, its low cetane number and high heat of vaporization prevent self-ignition in diesel engines [129-131]. Figure 4 shows that the United States generates almost 57% of bioethanol, while Europe accounts for only 6%. Each country's share is less than 27%, with Brazil being the second greatest producer [132,133]. The net heating value of ethanol is approximately 33% lower than that of gasoline when measured by volume, as shown in Table 5. The NHV, which is the same as the lower heating value or the net heat of combustion, indicates that as the proportion of ethanol increases in a fuel blend, the energy content decreases. Consequently, engines using ethanol-blended fuel will experience a reduction in miles per gallon (mpg) and driving range for a set tank size. However, this decrease in fuel economy can be somewhat compensated for by enhanced thermal efficiency. The engine’s full load torque and the heat discharged each cycle are proportional to the quantity of fresh air confined in each cycle and the fuel’s heating value per mass of that air. Standard gasoline and pure ethanol display comparable net heating values per mass of air under stoichiometric conditions, suggesting that the engine's torque per mass of air should be similar, assuming equal TEs. The enthalpy of vaporization indicates the energy needed to vaporize a liquid fuel. In DIEs, the cooling effect on the incoming air charge and the resulting suppression of engine knock due to fuel evaporation are linked to the amount of fuel per mass of air. Ethanol has a stoichiometric air–fuel ratio of 9.0, while that of gasoline is approximately 14.6, which varies with its composition. This means that, at stoichiometric levels, a greater mass of ethanol is required for a given mass of air than for gasoline. The heat of vaporization of ethanol is approximately 2.6 times greater than that of gasoline per unit mass of fuel and approximately 4.2 times greater per unit mass of a stoichiometric mixture. Ethanol has a lower molecular weight (46 g/mole) than typical gasoline hydrocarbons (95 - 115 g/mole), resulting in ethanol having a higher mole fraction in a blend than what would be suggested by its volume fraction alone. The addition of ethanol to gasoline leads to an increase in the vapour pressure of the mixture [134].

Ethanol works well as an alternative to gasoline in engines that start with a spark. It helps prevent the fuel from igniting too soon and can be used on its own or mixed with regular fossil fuels due to its physical and chemical properties [136-138]. Ethanol has gained significant attention as an alternative fuel due to its potential to substantially reduce greenhouse gas emissions and reduce dependency on traditional fossil fuels [139-142]. It is regarded as a clean and renewable liquid fuel produced from biomass resources such as lignin, fungi, cellulose, and xylose through the process of fermentation [143,144]. Ethanol, an oxygen-rich compound, has been demonstrated to emit lower levels of particulate matter and substantially decrease greenhouse gas emissions. The oxygen content in ethanol contributes to more complete combustion of the fuel, enhancing the combustion process [145]. The high octane content of ethanol and its ability to burn cleanly make it a popular fuel additive and an alternative to gasoline [146]. Moreover, ethanol fuel can be used in current gasoline engines with no or minimal modifications, making ethanol fuel a promising alternative fuel option [147]. Ethanol has a low stoichiometric air-fuel ratio, high oxygen content, and high H/C ratio. These factors collectively contribute to improving combustion efficiency [148,149]. Additionally, it has been found that the high latent heat of ethanol lowers the charge temperature, which can improve the combustion process. This effect also helps in moderating peak pressure and reducing the tendency for engine knocking [150]. Blending ethanol with gasoline has been shown to enhance the chemical composition of soot precursors. This promotes the formation of low-molecular-weight polycyclic aromatic hydrocarbons (PAHs) in aromatic flames and increases the oxidation of aliphatic flames during the combustion process [151]. Additionally, this blending process can increase the percentage of oxygen available for combustion, leading to lower emissions [152,153]. Recently, studies have shown that the use of ethanol-gasoline blends in modern SI engines enhances both engine performance and emissions. This has led to the extensive use of this fuel in SI engines as a substitute for traditional fuels [154].

Table 4
Previous studies on HCNG

Study ID	Engine Type	(CNG-HCNG) %	Performance Improvements	Performance Declines	Fuel Consumption Changes	Emissions Reductions	Emissions Increases
Lather and Das [78]	Multicylinder SI Engine	- (CNG, HCNG 10%, HCNG 18%)	Torque and power improvements were observed for HCNG 10% and HCNG 18% in comparison to CNG, with up to 6% torque benefits and up to 4% power benefits.	-	Reduced FEC and improved fuel conversion efficiency were observed for HCNG blends in comparison to CNG.	CO, HC, and CO2 emissions were reduced for HCNG blends in comparison to CNG.	An increase in NOx emissions was observed for HCNG blends in comparison with CNG, due to the higher combustion temperatures associated with hydrogen content.
Singh *et al.,* [100]	Heavy Duty Six Cylinder Engine	CNG & HCNG	-	-	-	Using HCNG fuel leads to notable decreases in unregulated emissions, including Formaldehyde, Acetylene, Formic Acid, Benzene, Ethane, and Propane. Additionally, regulated emissions such as CO, NO, HC, and PM are significantly lowered with HCNG fuel.Top of Form	With HCNG fuel, there's a slight rise in Methanol, Ethanol, Formaldehyde, and Acetaldehyde emissions. Additionally, an increase in NH3 and NO2 with HCNG fosters conditions conducive for the efficient operation of exhaust after-treatment devices such as Selective Catalytic Reduction (SCR) systems in Euro VI compliant vehicles.
Duan *et al.,* [101]	Large Bore, Lean Burn Natural Gas SI Engine	Hydrogen Enrichment	With a higher percentage of hydrogen energy share, there's a decrease in cycle-to-cycle variations in IMEP. The coefficient of	-	-	-	-

			variation of the peak combustion pressure dropped from 8.75% (without hydrogen) to 2.82% (with a 27.68% hydrogen energy share). The average start of combustion advanced as the hydrogen ratios increased, although the cycle-to-cycle variations of it remained relatively unchanged. Additionally, the combustion duration was shorter, and its cycle-to-cycle variations were reduced by 5.4% with a 27.68% hydrogen energy share. Top of Form				
Prasad *et al.,* [102]	Single-cylinder water-cooled CIDI engine modified for HCNG	- (HCNG; mixture of H2 and CNG)	LI mode exhibited lower coefficient of variation in IMEP (COVIMEP) compared to SI mode, indicating better combustion stability with LI. Optimal MBT timing achieved at 31° CA bTDC for HCNG mixtures, leading to improved engine performance, combustion, and emission characteristics.	-	-	At 31 degrees (°CA bTDC) Minimum Spark Timing for Best Torque, both reduced emissions and enhanced BTE were noted in comparison to other spark timings.	-
Prasad and Agarwal [103]	Single-cylinder naturally aspirated water-cooled	CNG, H2, HCNG mixtures	In LI mode, BTE improved from 36.9% to 37.82% for CNG and from 37.7% to 38.6% for a 40% HCNG.	Pmax reduced with H2 enrichment of CNG, from 47.62 bar	BSFC in LI mode decreased from 0.20	EGT reduced in LI mode. At 0.15 bar boost, BSCO and BSNOx emissions	-

	direct injection diesel engine adapted/modified to supercharged SI/LI PFI gaseous fueled engine		Additionally, torque in LI mode experienced an increase compared to SI mode, rising from 29 Nm to 32.5 Nm for CNG and from 20 Nm to 24 Nm for Hydrogen (H2). Top of Form	for CNG to 39.77 bar for 40%HCNG.	kg/kWh for CNG to 0.180 kg/kWh for a 40% HCNG.	reduced with H2 enrichment.	
Leng *et al.,* [104]	Medium-speed NG engine with prechamber initiated turbulent jet ignition	HCNG; mixture of H2 and CNG	Improved combustion and performance due to hydrogen enrichment. Combustion rates enhanced by turbulent jets and chemical dynamics of hydrogen-enriched fuel.	-	Indicated SFC decreases with increased hydrogen fraction.	Reductions in CO, total HC, and nonmethane HC emissions. Significant decrease in emissions with up to 30% hydrogen enrichment.	Increase in nitrogen oxides emissions with increased hydrogen fraction due to higher combustion temperatures.
Prasad and Agarwal [105]	CVCC	HCNG mixtures	LI of HCNG enables lean-burn combustion, key for future emissions norms compliance. Hydrogen enrichment of CNG overcomes low volumetric energy density and flame speed limitations, improving lean flammability limits.	-	-	-	-
Hao *et al.,* [106]	6-cylinder CNG engine modified for HCNG operation	0%, 20%, 40% HCNG	Enhanced and advanced combustion stability with hydrogen blending. Improved engine performance and efficiency.	-	Reduced BSFC with optimal excess air ratio and ignition advance angle.	Reduction in CO and CH4 emissions with hydrogen blending.	Increased NOx emissions with increased hydrogen fraction due to higher combustion temperatures.
Zhang *et al.,* [107]	Single-cylinder, water-cooled,	CNG, HCNG blends	LI enabled lean-burn combustion, improving	-	-	Significant contribution of	-

	direct injection diesel engine adapted for HCNG operation		particulate emission characteristics, especially in nucleation mode particle size range. particulate emission characteristics, particularly within the nucleation mode particle size range			lubricating oil in particulate emissions from both hydrogen and HCNG fueled LI engines. Reduced particulate number concentration with hydrogen enrichment in CNG, particularly at higher engine loads.	
Zareei *et al.,* [108]	6-cylinder CNG engine modified for HCNG operation	0%, 20%, 40% HCNG	Enhanced and advanced combustion stability with hydrogen blending. Improved engine performance.	-	Reduced BSFC with optimal excess air ratio and ignition advance angle.	Reduction in CO and CH4 emissions with hydrogen blending.	Increased NOx emissions with increased hydrogen fraction attributable to elevated combustion temperatures.
Prasad and Agarwal [109]	Single-cylinder water-cooled CIDI engine modified for HCNG operation	HCNG mixtures	In LI mode, HCNG showed a higher Pmax, with its peak occurring closer to Top Dead Center. The addition of hydrogen to CNG resulted in an increase in Pmax by approximately 2.9 bar, Rate of Pressure Rise by approximately 0.72 bar/degree, and Heat Release Rate by approximately 7.2 kJ/m^3.degree for a 40% HCNG compared to the baseline CNG. The highest BTE was recorded at approximately 42.8% (at	-	The lowest BSFC was achieved at λ = 1.2 for HCNG in SI mode, while in LI mode it was achieved at λ = 1.4.	BSHC emissions were lower in LI mode than SI mode. At 3.96 bar BMEP, BSHC emissions reduced from 0.54 g/kWh (for CNG) to 0.35 g/kWh (for 40HCNG), further reduced to 0.21 g/kWh (for H2) in LI mode. BSNOx emissions increased with increasing BMEP but reduced from 0.89 g/kWh at λ = 1.5 for CNG to 0.17 g/kWh for 30HCNG at λ = 1.7 at 30 Nm load.	-

			an excess air ratio λ = 1.4) in LI mode for an engine fueled with a 30% HCNG.				
Park *et al.,* [110]	11-L CNG Engine Modified for HCNG Operation	6–10% HCNG	Adding 6–10% hydrogen enables similar levels of torque and BSFC compared to the base engine with the same lambda condition. The virtual HCNG engine achieves performance and emission similar to those of the base engine under the middle speed operation range.	At 1000 rpm, NOx formation is greater than base engine condition, while a similar NOx level can be maintained under the middle speed range (1300 and 1500 rpm) despite hydrogen addition.	-	-	Increased NOx emissions at low rpm due to elevated combustion temperatures with hydrogen addition, but manageable at middle speeds.
Barbu *et al.,* [111]	Multicylinder SI Engine	CNG, HCNG 10%, HCNG 18%.	Torque and power improvements were observed for HCNG 10% and HCNG 18% in comparison to CNG, with up to 6% torque benefits and up to 4% power benefits.	-	Reduced fuel energy consumption and improved fuel conversion efficiency were observed for HCNG blends in comparison to CNG.	CO, HC, and CO2 emissions were reduced for HCNG blends in comparison to CNG.	An increase in NOx emissions was observed for HCNG blends in comparison with CNG, due to the higher combustion temperatures associated with hydrogen content.
Duan *et al.,* [112]	Heavy-duty lean-burn NG SI engine	LP, HP, Combined HP-LP, Internal EGR.	Combined 10% HP EGR with 5% LP EGR ratio improved indicated thermal efficiency	Peak combustion pressure decreased with increased EGR ratio	-	NOx emissions lowest with HP EGR system	-
Luo *et al.,* [113]	-	Various HCNG blends	Hydrogen addition to CNG increases the laminar burning velocity of the mixture, boosting combustion efficiency	-	At optimal conditions, hydrogen enrichment leads to	Significant reductions in CO, THC, and CH4 (Methane) emissions due to improved combustion efficiency	Increased NOx emissions due to higher combustion temperatures resulting from hydrogen

			and reducing brake specific fuel consumption. Optimal conditions (excess air ratio and spark timing) lead to an increase in BTE and significant reduction in cycle-by-cycle variations.		improved fuel efficiency.	with hydrogen enrichment.	addition. Optimized ignition timing and excess air ratio can achieve higher thermal efficiency with low NOx emissions under emission regulation limits.
Hora and Agarwal [114]	Single-cylinder prototype HCNG engine	Various HCNG blends (0%, 10%, 20%, 30% HCNG)	Improved BTE, reduced BSFC, BSEC, and enhanced combustion stability.	-	Across all load conditions, BTE experienced an uptick with the augmentation of hydrogen content in HCNG blends, attributable to the enhanced combustion efficiency and improved combustion stability provided by the hydrogen addition.	Reduction in HC, CO, and CO2 emissions.	Increase in NO emissions with hydrogen addition at a given BMEP, with 30% HCNG showing the best performance and emission benefits among the tested HCNG mixtures.
Li *et al.,* [115]	Lean-burn marine NG engine	Hydrogen-rich reformate addition)	Enhanced lean-burn limit, improved combustion efficiency	-	-	Decrease in THC emissions with increased reformate addition.	Initial increase then decrease in NOx emissions with reformate addition; Increase in CO

							emissions under larger λ.
Sopena *et al.,* [116]	Volkswagen Polo 1.4 converted to hydrogen operation	- (Hydrogen)	Increased brake torque of 63 Nm at 3800 rpm and maximum brake power of 32 kW at 5000 rpm. Greater brake thermal efficiency compared to gasoline, especially at lean conditions (λ = 2.5) and high speeds (above 4000 rpm).	-	-	Significant reduction in CO, THC, and CH4 (Methane) emissions due to improved combustion efficiency.	Increased NOx emissions with richer mixtures (λ < 2) due to higher combustion temperatures.
Wasiu *et al.,* [117]	Direct Injection Spark Ignition Engine	0, 20, 28, 38, 46% by volume	-	-	Increase in BSEC with higher hydrogen percentages.	Decrease in BSCO and BSUHC emissions with increasing percentage of hydrogen gas. Significant reduction of approximately 94% and 26% between rich and stoichiometric mixtures, respectively.	Increase in BSNOx emission concentrations as the percentage of hydrogen gas increases due to enhanced turbulence within the engine cylinder leading to higher combustion temperatures.
Lather and Das [78]	Multicylinder Spark Ignition (SI) Engine	CNG, HCNG 10%, HCNG 18%	Torque and power improvements for HCNG 10% and HCNG 18% in comparison to CNG, with up to 6% torque benefits and up to 4% power benefits.	-	Reduced fuel energy consumption and improved fuel conversion efficiency for HCNG blends in comparison to CNG.	CO, HC, and CO2 emissions were reduced for HCNG blends in comparison to CNG.	An increase in NOx emissions was observed for HCNG blends in comparison with CNG, due to the higher combustion temperatures associated with hydrogen content.
Sagar and Agarwal [48]	Port fuel injected; HCNG fueled SI engine	CNG, 10%, 20%, 30%, 50%, 70% HCNG mixtures, and hydrogen	Lower knocking intensity exhibited by 30% HCNG across all loads.	-	-	Lower emissions of CO2, HC, and CO with HCNG compared to baseline CNG.	Higher NOx emissions with HCNG due to the higher combustion temperatures

							associated with hydrogen content.
Yu *et al.,* [119]	Gasoline/hydrogen SI engine with hydrogen direct injection (HDI) and gasoline port injection	Gasoline plus homogeneous hydrogen and gasoline plus stratified hydrogen	Stratified hydrogen leads to more stable and faster ignition, speeding up the combustion rate, achieving higher brake thermal efficiency, especially under lean burn condition.			Homogeneous hydrogen reduces HC and NOx emissions.	Stratified hydrogen mode increases NOx and HC emissions by 14.3% and 12.8% on average compared to homogeneous hydrogen due to denser hydrogen concentration near the sparking plug and higher combustion temperatures.
Pandey *et al.,* [120]	SI engine with fixed ignition timing	CNG, 5HCNG, 10HCNG, 15HCNG	Significant reduction in CO, CO2, and HC emissions with higher hydrogen fraction. Improved BTE observed with higher hydrogen content.	-	-	CO, CO2, and HC emissions were reduced with higher hydrogen content in HCNG blends.	-

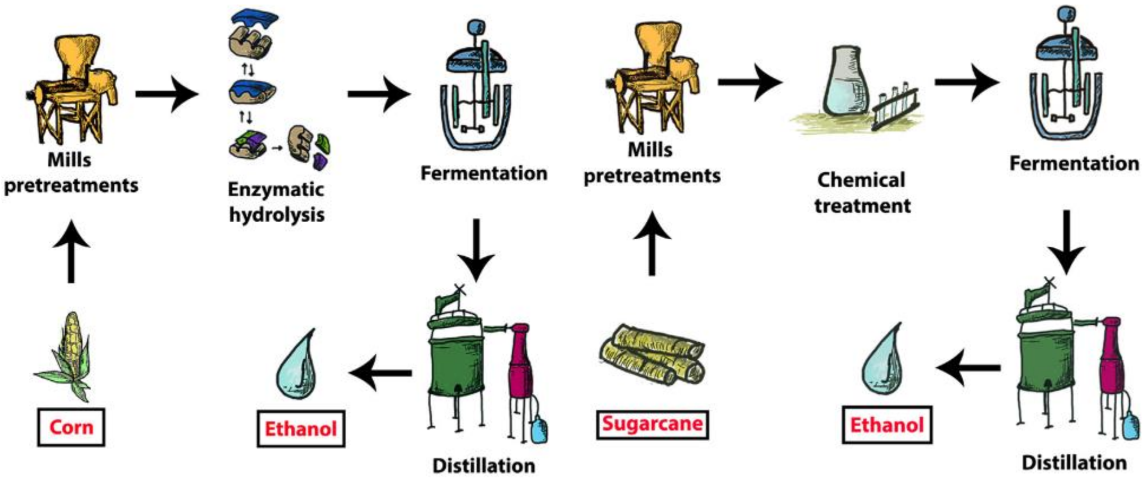

Fig. 3. First-generation process for ethanol production from (a) starchy and (b) saccharose materials [131]

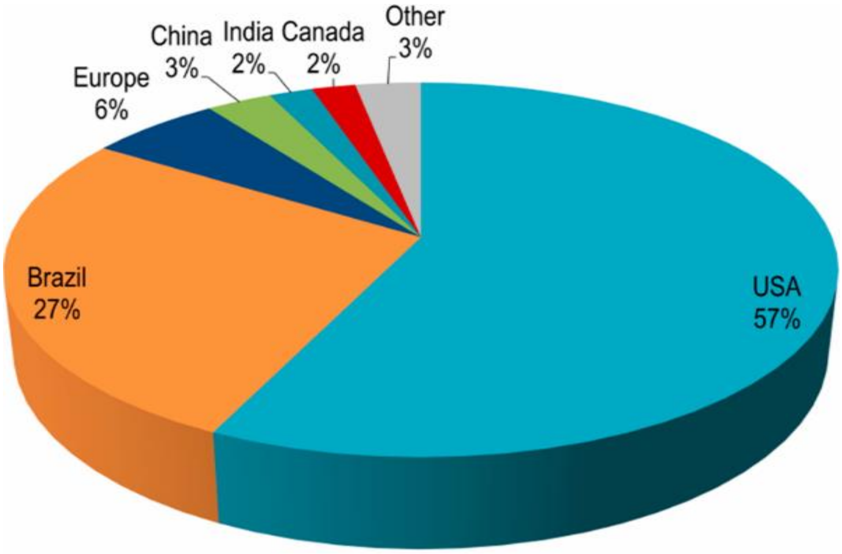

Fig. 4. Global bioethanol production [133]

Table 5
Properties of the pure gasoline and ethanol fuels [135]

Property	Gasoline Value	Ethanol Value
RON	91-93	109
MON	81-84	90
AKI	87-88	99
Density (kg/L)	(0.72-0.78)	0.79
Stoichiometric air-fuel ratio (kg/kg)	14.6	9.0
NHV (MJ/kg fuel) [at ASTM]	44	27
(MJ/L fuel)	33	21
(MJ/kg stioch. mix)	2.8	2.7
HoV (MJ/kg fuel) [at 25 °C]	0.35	0.92
(MJ/L fuel)	0.26	0.72
(MJ/kg stioch. mix)	0.022	0.092
(MJ/MJ NHC)	0.0080	0.034
RON	91-93	109
MON	81-84	90
AKI	87-88	99
Density (kg/L)	(0.72-0.78)	0.79

3.1 Effect of Ethanol-Gasoline Blends on the Performance and Emissions of SI Engines

Experimental research on ethanol-petrol fuel blends was conducted using a single-cylinder, four-stroke petrol engine with four fuels—neat petrol and three ethanol blends (E20, E40, and E60). The E20 blend achieved the highest brake power at 24° bTDC under full load conditions. An improvement in the CR and TE was observed with ethanol blending, with the E20 blend displaying superior thermal efficiency. Additionally, an increase in the percentage of ethanol led to a decrease in HC emissions, especially for the E60 blend at 24° bTDC [155]. The introduction of ethanol-gasoline blends (E0, E5, E10, E15, and E20) was found to slightly increase brake power and reduce brake specific fuel consumption, with improvements observed in brake thermal efficiency and volumetric efficiency. While CO2 and NOx emissions increased with the addition of ethanol, CO and HC emissions decreased [156]. Experiments on a single-cylinder SICI engine with a high CR showed that ethanol blending enhances combustion stability, engine power, and efficiency, notably achieving a 15.1% increase in IMEP and a 9.1% improvement in ITE with pure ethanol compared to nonblended fuel. When NOx emissions increased due to higher combustion temperatures, THC emissions decreased. The impact of ethanol on particulate emissions was mainly observed in the distribution of particle sizes rather than a reduction in total particulate numbers [157]. In research utilizing a 1-L four-stroke three-cylinder T-GDI engine, the effects of ethanol-gasoline blends on engine performance were examined. The rate of spray development initially increased with the addition of ethanol, attributed to its higher density and viscosity, but this trend reversed as a result of the vaporization characteristics of ethanol. Although the brake-specific fuel consumption (BSFC) of ethanol was found to be 28.7% higher than that of gasoline, ethanol blends, particularly E85 and E100, exhibited lower brake-specific energy consumption (BSEC), indicating enhanced power efficiency. Additionally, blends exceeding the E50 effectively suppressed engine knock, with blends containing higher ethanol contents, such as E85 and E100, experiencing no knocking due to ethanol's higher octane number [158]. A study on the Honda GX200-DQX engine examined the impact of varying ethanol-gasoline blends (E00, E10, E20, E30, and E40) on engine performance, highlighting differences in the indicated power, thermal, mechanical, and volumetric efficiencies. The findings revealed that E40 delivered the highest indicated power at moderate speeds, while E30 led at higher speeds. The thermal efficiency peaked with E40 at lower speeds, whereas pure gasoline (E00) was superior at higher speeds. The mechanical efficiency was optimal with lower ethanol contents, particularly for E20, at higher speeds. Higher ethanol blends resulted in reduced volumetric efficiency, especially at elevated speeds, indicating that ethanol blending can enhance engine performance, with the suitability of specific blends varying by speed and load [159].

A study conducted on a Toyota Tercel-3A SI engine using ethanol-unleaded gasoline blends demonstrated that ethanol addition notably enhanced engine performance. Key improvements included an 8.3% increase in brake power, a 9.0% increase in brake thermal efficiency, and a 7% increase in volumetric efficiency on average. Although fuel consumption increased by approximately 5.7%, the BSFC and air-fuel ratio decreased by approximately 2.4% and 3.7%, respectively. The study also reported a significant decrease in CO and HC emissions of 46.5% and 24.3%, respectively, but CO2 emissions increased by 7.5%. The 20% ethanol blend emerged as the most effective mixture [160]. Building on these findings, a study on a 1.3-L four-cylinder gasoline direct injection (GDI) engine examining ethanol-gasoline blends (E10, E20) and reformed exhaust gas recirculation (REGR) revealed enhancements in engine performance and emissions. BSEC and BTE improved by up to 11% and 12.4%, respectively. The emissions of CO and NOx decreased by up to 38% and 86%, respectively. Additionally, a significant reduction, up to 48%, was observed in total PM, especially in the accumulation mode, with the E20 blend [161]. When using a single-cylinder SI engine (TD 200) with ethanol-gasoline blends (10%, 20%, 30%, 40%), key findings included an increase in the research octane number (RON) and motor octane number (MON) for all blends. The E40 blend demonstrated the greatest improvement, with a 25.8% increase in the TE and a 17.21% reduction in the BSFC. Additionally, exhaust emissions significantly decreased with increasing ethanol ratios, notably in E30 for CO (26.33%), in E40 for CO2 (25%), HC (31.05%), and NOx (20.91%) [162]. The impact of ethanol-gasoline blends (E50 and E85) on a single-cylinder, four-stroke SI engine with variable CRs (10:1 and 11:1) showed that these blends led to an increase in engine torque of approximately 2-2.8% and an increase in BSFC of 16.1-45.6%, depending on the blend and CR. Reductions in CO and HC emissions were noted, with HC emissions decreasing by up to 24% at a 10:1 CR due to ethanol's leaning effect and oxygen content. Ethanol blends also resulted in lower NOx emissions than did pure gasoline, a benefit attributed to ethanol's high latent heat of vaporization. These findings underline the role of ethanol in increasing engine efficiency and lowering emissions [126].

A study on the effects of varying CRs and spark timings on a two-wheeler using E30 fuel under wide-open-throttle conditions showed increases in in-cylinder pressure and heat release rate with higher CRs, enhancing combustion and shortening its duration. The power improved by an average of 2.5% and 4.5% for CRs of 10.9:1 and 11.5:1, respectively, with a peak increase of 8.0% at a CR of 11.5:1 and a 4 °CA spark advance. The specific fuel consumption decreased by 6.0% and 8.9% for these ratios, reaching a maximum decrease of 13%. Reductions in CO and HC emissions were significant, by up to 52% and 43%, respectively, while NOx emissions increased by up to 32% with an optimized 4 °CA spark advance [163]. The effects of ethanol-blended gasoline (E5, E10, and E15) on engine performance and emissions with a four-stroke SI EF7 engine showed that ethanol blends led to decreases in power and torque of 5.79%, 1.89%, and 1.57% for E5, E10, and E15, respectively, and increased fuel consumption of 3.34% for E5, with further increases of 3.79% and 1.45% for E10 and E15, respectively. The volumetric efficiency also decreased with the use of ethanol, by 6.32%, 1.85%, and 3.05% for E5, E10, and E15, respectively. However, the emissions of CO, CO2, and HC significantly decreased as the ethanol content increased, with E15 demonstrating the most notable improvement in emissions. The findings suggest that E10 and E15 are viable substitutes for gasoline in urban settings, offering comparable performance but with lower emissions [164]. A study conducted on a four-stroke single-cylinder multifuel engine with variable compression utilizing ethanol-blended fuels (E0, E5, E10, and E20) revealed that ethanol blends significantly improve engine efficiency. The best brake power was observed with the E20 blend, demonstrating a 5% increase in brake power with 10% ethanol. The highest thermal efficiency was recorded at 24.5% for E20, with E10 and E5 closely behind. The inclusion of ethanol was shown to enhance brake thermal efficiency and decrease specific fuel consumption, highlighting ethanol's viability as a gasoline alternative for better engine performance and lower emissions [165].

An experimental study conducted on a 4-cylinder, 4-stroke, 1.8-liter Mazda Premacy MPFI engine comparing pure gasoline (E0) with a 15% ethanol-gasoline blend (E15) indicated changes in gaseous emissions due to ethanol blending. Although E15 led to higher NOx and CO2 emissions, it effectively reduced CO and HC emissions. Specifically, at 1000 rpm, the UHC emissions for E15 were 289 PPM greater than those for E0, although this difference narrowed at increased speeds, with both E0 and E15 showing reduced UHC emissions as the engine speed increased. At 4000 rpm, NOx emissions for E15 were 232 PPM lower than those for E0, highlighting the ability of ethanol to lower certain emissions under specific operating conditions [166]. In a study conducted using a four-stroke, four-cylinder MPFI SI engine, the effects of ethanol-premium gasoline blends on engine performance were explored, focusing on brake torque, BP, and BSFC across various speeds (2200, 3200, and 4200 rpm) and loads (5, 10, 15, and 20 kg). The F2 sample, containing 6.25% ethanol, exhibited optimal performance, achieving a maximum BT of 104 Nm at 3000 rpm and a 20 kg load, along with a peak

BP of 24.5 kW at 4200 rpm and a 20 kg load. Higher ethanol concentrations were associated with an increase in BSFC, with the F2 sample showing the lowest BSFC of 0.268 kg/kWh at 3200 rpm and a 20 kg load [167]. A study conducted on a turbocharged port fuel injection spark ignition engine assessed the impact of E85 fuel under various conditions, including dual fuel (DF) and mixed injection modes, with adjustments in air–fuel ratios and spark timings. It was observed that E85 facilitated advanced spark timing, significantly boosting the thermal efficiency to approximately 0.39, in contrast to 0.31 for gasoline. The presence of oxygen in ethanol, particularly in leaner mixtures, resulted in a marked decrease in CO and HC emissions, although NO emissions increased due to increased peak pressures. A notable reduction in particulate emissions (PN and PM1) was also documented with E85, especially in the mixed injection mode, highlighting its potential for enhancing engine performance and reducing emissions [168]. The previous studies of ethanol are provided in Table 6.

Table 6
Previous studies on Ethanol Blending

Study ID	Engine Type	Ethanol Blend (% Ethanol)	Performance Improvements	Performance Declines	Fuel Consumption Changes	Emissions Reductions	Emissions Increases
Kumbhar and Khot [155]	Single-cylinder, four-stroke petrol	E20, E40, E60	BP (E20), CR, TE	-	-	HC (notably E60)	-
Najafi *et al.,* [156]	Single-cylinder, four-stroke petrol	E0, E5, E10, E15, E20	BP, BTE, VE	-	Reduction in BSFC	CO, HC	CO2, NOx
Liu *et al.,* [157]	Single-cylinder SICI	Ethanol blends	Combustion stability, engine power, efficiency, IMEP, ITE	-	-	THC	NOx
Kim *et al.,* [158]	1-L T-GDI	Ethanol blends, especially E85, E100	Spray development, power efficiency, knock suppression	-	Higher BSFC for ethanol	-	-
Rao *et al.,* [159]	Honda GX200-DQX	E00, E10, E20, E30, E40	IP (E40 at moderate speeds, E30 at high speeds), TE (E40 at lower speeds, E00 at higher speeds), ME (lower ethanol contents, particularly E20 at higher speeds)	VE (reduced especially at elevated speeds with higher ethanol blends)	-	-	-
Al-Hasan [160]	Toyota Tercel-3A SI	E20	BP, TE, VE	-	Increase (~5.7%)	CO, HC	CO2
Chaimanatsakun *et al.,* [161]	1.3-L GDI	E10, E20	BSEC, BTE	-	-	CO, NOx, PM	-
Mohammed *et al.,* [162]	Single-cylinder SI (TD 200)	E10, E20, E30, E40	RON, MON, TE	-	Decrease (E40: 17.21%)	CO (E30), CO2, HC, NOx (E40)	-
Koç *et al.,* [126]	Single-cylinder, four-stroke SI	E50, E85	Engine torque (increase by 2-2.8%)	VE with higher blends	Increase (16.1-45.6%)	CO, HC (up to 24% reduction at 10:1 CR), NOx	-
Sakthivel *et al.,* [163]	Two-wheeler, single-cylinder SI	E30	BP, in-cylinder pressure, heat release rate	-	Decrease (6.0-13%)	CO, HC	NOx
Hosseini *et al.,* [164]	Four-stroke SI EF7	E5, E10, E15	-	BP, T, VE	Increase (E5: 3.34%, E10: 3.79%, E15: 1.45%)	CO, CO2, HC	-

Kumar *et al.,* [165]	Four-stroke single-cylinder multifuel	E5, E10, E20	BP, TE	-	-	-	-
James *et al.,* [166]	Mazda Premacy MPFI	E15	-	-	-	CO, HC	NOx, CO2
Verma *et al.,* [167]	Four-cylinder MPFI SI	~E6.25 (F2 sample)	BT, BP	-	Increase in BSFC	-	-
Tornatore *et al.,* [168]	Turbocharged PFI SI engine	E85	TE	-	-	CO, HC, PM	NO

4. Development of Recent Research on Conventional Fuel

The growing concern surrounding the depletion of fossil fuels and the consequent search for renewable alternatives boasting efficiencies comparable to those of conventional fuels. The potential and opportunities for alternative fuels across various applications are discussed. As a substitute for fossil fuels, researchers are investigating several substances sourced from natural sources, particularly those derived from petroleum-based fuels [169]. Fossil fuels play a crucial role in the global economy, but they also pose significant environmental risks, including GHG emissions. Transitioning to cleaner energy alternatives presents considerable challenges. Nevertheless, it is imperative to decrease or completely phase out fossil fuel usage to safeguard our planet [170]. Internal combustion engines, fuelled by oil, generate roughly a quarter of the world's energy, translating to approximately 3000 out of 13,000 million tons of oil equivalent annually. This process is responsible for approximately 10% of global greenhouse gas emissions [171]. Fossil fuels represent a significant portion of the total energy generated from renewable sources. There is no alternative energy source available that can substitute for fossil fuels. Renewable energy sources provide a total capacity of 1350 gigawatts (GW) from hydropower, 336 GW from wind, 150 GW from solar, and 20 GW from geothermal sources. Additionally, farmers produce 17.5 million tons (Mt) of bioethanol and 2.45 Mt of biodiesel each year. However, even with a combined renewable output of 1856 GW, these sources, excluding hydro, meet only approximately 20% of the world's energy requirements, with the remaining 80% still reliant on fossil fuels. The rate at which renewable energy is being harnessed scarcely keeps pace with the increasing demand for energy [172]. Therefore, it is advisable for nations pursuing hydrogen energy to implement tailored policies that empower the government to support and regulate the integration of hydrogen fuel cells into their power generation portfolio. Establishing such policies is crucial because they lay the foundation for the governance, innovation, and administration of alternative energy sources within a country [173].

Recent research developments in conventional fuels underscore a critical reality: Despite the significant advancements and increased utilization of new and renewable energy sources, the complete elimination of fossil fuels from our energy portfolio remains an unattainable goal in the near future. This enduring reliance on fossil fuels is driven by a combination of factors, including their entrenched role in our global energy infrastructure, the economic feasibility of extracting and utilizing these resources, and the technological challenges and scale of investment required to fully transition to alternative energy sources [174-177]. Fossil fuels, including coal, NG, and oil, have historically powered industrial growth, electricity generation, transportation, and heating for centuries [178]. Their high energy density, ease of transport and storage, and well-established extraction and consumption technologies make them difficult to replace in the short term [179]. Furthermore, the global economy's deep entrenchment in fossil fuel exploitation means that any transition to renewable energy sources must contend with significant economic and social implications [180]. The development of renewable energy technologies, such as solar, wind, hydroelectric, and geothermal power, has certainly made impressive strides, offering cleaner, more sustainable alternatives to traditional fossil fuel sources. However, the intermittency of renewable energy, coupled with challenges in energy storage and grid integration, underscores the need for a diverse energy mix that continues to include fossil fuels as a reliable baseload power source [181].

5. Results and Discussion

The assessed efforts encompass the use of natural gas, HCNG which is hydrogen-enriched natural gas, and ethanol-gasoline mixture. In each subsection, literature is cited to explain the improvements in engine performance and reductions of emissions compared to normal operation using conventional gasoline. Also, it offers ideas about the kind of advices concerning the utilization of these other fuels in IC engines, both the positive aspects together with the negative aspects with reference to them. The finding from those studies is designed to inform the further research and development to make better advances of IC engines with higher efficiency and sustainability.

5.1 Natural Gas in SI Engines

Natural gas is proved to increase engine performance and reduce emissions, various studies have proved that that compressed natural gas (CNG) engines can achieve higher thermal efficiency and lower emissions compared to gasoline engines. Key findings from these studies include

i. Performance: CNG engines provide higher engine efficiency and lower brake-specific fuel consumption (BSFC).
ii. Emissions: CNG engines produce lower levels of carbon dioxide (CO2), hydrocarbons (HC), and nitrogen oxides (NOx) compared to gasoline engines.
iii. Challenges: CNG engines often face issues related to lower brake power and cold start performance.

5.2 Hydrogen-Enriched Natural Gas (HCNG)

HCNG have been studied for their potential to improve engine performance and reduce emissions. The key findings from these studies include

i. Performance: HCNG blends have improved brake thermal efficiency, torque, and power output. Blends with 10% and 18% hydrogen by volume provide significant benefits.
ii. Emissions: HCNG blends reduced carbon monoxide (CO), hydrocarbons (HC), and CO2 emissions compared to pure CNG but it increased NOx emissions due to higher combustion temperatures.

5.3 Ethanol in SI Engines

Ethanol-gasoline blends have been studied for their effect on engine performance and emissions. The key findings from these studies iclude:

i. Performance: Ethanol blends, such as E10 and E20, enhance brake thermal efficiency and engine power. Higher ethanol content can also improve combustion stability.
ii. Fuel Consumption: Ethanol blends can result in a slight increase in fuel consumption due to their lower energy density compared to gasoline.
iii. Emissions: Ethanol blends reduce CO and NOx emissions significantly. Additionally, ethanol has been found to lower particulate matter emissions.

5.4 Suggestions for Better using Alternative Fuels in Engines

i. Compressed Natural Gas (CNG): Cold start performance through preheating systems and advanced fuel injection strategies should be improved.

ii. Hydrogen-Enriched Natural Gas (HCNG): Specific blend ratios of hydrogen and natural gas should be optimized to maximize efficiency and minimize emissions, and effective emissions control technologies should be Integrated to mitigate the increase in NOx emissions.
iii. Ethanol: Ethanol blend ratios for different engine designs and operating conditions should be optimized to enhance performance and reduce emissions.

6. Conclusions

The main advantages and disadvantages of the employment of different kinds of fuels specially in SI engines is also elaborated in this review. The cleaning capability of Hydrogen, natural gas and ethanol has a vast potential in reducing emissions and also effectively enhances the overall performance of this Engine. Putting together the preceding arguments, therefore, this post supports the continued research and development of IC engines that rely on efficient alternative fuels to solve the energy crises of the 21 st century IC engines market. Fossil fuels contribute to air pollution and greenhouse gas emissions, which are leading environmental concerns. With fossil fuel resources dwindling and GHG levels rising, there is an urgent need to adopt alternative fuels that are both environmentally friendly and equally efficient. In this review, various alternative fuels are studied to determine their effects on both SI engine performance and emissions, particularly HCNG, CNG, and ethanol. These types of fuels reduce harmful emissions, yet they also present challenges, especially in terms of engine performance and emissions. Adopting these fuels is straightforward because they do not require major redesigns of engines, leading to their broad and extensive use. Switching to alternative fuels is not just about moving away from gasoline; it is a whole new way of thinking about what drives our cars, making sure these greener fuels work well without losing any get-up-and-go. Although alternative fuels have shown promise in improving engine efficiency and reducing emissions, completely replacing fossil fuels as the main energy source remains a challenge. This is mainly because fossil fuels, with their high energy density and established global supply chains, remain integral to the world’s energy infrastructure. The transition to alternative fuels requires overcoming technological, economic, and logistical hurdles. Additionally, existing energy systems and engines are predominantly designed for fossil fuels, making a swift transition challenging without substantial investments in new technologies and infrastructure. The future will likely involve a diversified energy mix, where conventional and renewable energies coexist to sustainably meet global demand.

The main results of this study are summarized as follows

i. The improvement in brake thermal efficiency and reduction of CO and HC emissions occur when using HCNG blends, but it causes an increase in NOx emission.
ii. Compared to gasoline, hydrocarbon emissions and energy consumption are reduced on CNG engines but have brake power reduction and cold start problems.
iii. Ethanol blends in gasoline often improve brake thermal efficiency with benefits on CO and NOx emission but slightly increase fuel consumption.

Acknowledgement

This research was not funded by any grant.

References

[1] Nasir, Rabiya, Hui Meng, Sajid Rashid Ahmad, Liaqat Ali Waseem, Syed Ali Asad Naqvi, Muhammad Shahid, Khizra Nasir et al. "Towards sustainable transportation: A case study analysis of climate-responsive strategies in a developing nation." *Case Studies in Thermal Engineering* 55 (2024): 104117. https://doi.org/10.1016/j.csite.2024.104117

[2] Alsunousi, Mohammed, and Erhan Kayabasi. "The role of hydrogen in synthetic fuel production strategies." *International Journal of Hydrogen Energy* 54 (2024): 1169-1178. https://doi.org/10.1016/j.ijhydene.2023.11.359

[3] Asif, Muhammad, and Tariq Muneer. "Energy supply, its demand and security issues for developed and emerging economies." *Renewable and Sustainable Energy Reviews* 11, no. 7 (2007): 1388-1413. https://doi.org/10.1016/j.rser.2005.12.004

[4] Armaroli, Nicola, and Vincenzo Balzani. "Towards an electricity-powered world." *Energy & Environmental Science* 4, no. 9 (2011): 3193-3222. https://doi.org/10.1039/c1ee01249e

[5] Annasaheb, Kardile Balasaheb, Khizar Ahmed Pathan, Abhijeet Bhikashet Auti, and Sher Afghan Khan. "Simulation of Energy Dissipation in BLDC Motor and Analysis of Speed-Acoustic Characteristics." *Journal of Advanced Research in Applied Mechanics* 111, no. 1 (2023): 38-61. https://doi.org/10.37934/aram.111.1.3861

[6] Ghazaly, Nouby, and Mohamed Salah Hofny. "Injection and Combustion of biodiesel at different blends: A review." *SVU-International Journal of Engineering Sciences and Applications* 3, no. 2 (2022): 37-46. https://doi.org/10.21608/svusrc.2022.130956.1043

[7] Awogbemi, Omojola, Daramy Vandi Von Kallon, Emmanuel Idoko Onuh, and Victor Sunday Aigbodion. "An overview of the classification, production and utilization of biofuels for internal combustion engine applications." *Energies* 14, no. 18 (2021): 5687. https://doi.org/10.3390/en14185687

[8] Zhao, Fuquan, Kangda Chen, Han Hao, and Zongwei Liu. "Challenges, potential and opportunities for internal combustion engines in China." *Sustainability* 12, no. 12 (2020): 4955. https://doi.org/10.3390/su12124955

[9] Jacob, Ashwin, and B. Ashok. "An interdisciplinary review on calibration strategies of engine management system for diverse alternative fuels in IC engine applications." *Fuel* 278 (2020): 118236. https://doi.org/10.1016/j.fuel.2020.118236

[10] Tian, Zhi, Xudong Zhen, Yang Wang, Daming Liu, and Xiaoyan Li. "Comparative study on combustion and emission characteristics of methanol, ethanol and butanol fuel in TISI engine." *Fuel* 259 (2020): 116199. https://doi.org/10.1016/j.fuel.2019.116199

[11] Gong, Changming, Lin Yi, Zilei Zhang, Jingzhen Sun, and Fenghua Liu. "Assessment of ultra-lean burn characteristics for a stratified-charge direct-injection spark-ignition methanol engine under different high compression ratios." *Applied Energy* 261 (2020): 114478. https://doi.org/10.1016/j.apenergy.2019.114478

[12] Zhang, Zhiyuan, Zuohua Huang, Xiangang Wang, Jun Xiang, Xibin Wang, and Haiyan Miao. "Measurements of laminar burning velocities and Markstein lengths for methanol-air-nitrogen mixtures at elevated pressures and temperatures." *Combustion and Flame* 155, no. 3 (2008): 358-368. https://doi.org/10.1016/j.combustflame.2008.07.005

[13] Tunér, Martin. "Combustion of alternative vehicle fuels in internal combustion engines." *Report within Project* (2015).

[14] Masuk, Nahid Imtiaz, Khodadad Mostakim, and Shithi Dey Kanka. "Performance and emission characteristic analysis of a gasoline engine utilizing different types of alternative fuels: A comprehensive review." *Energy & Fuels* 35, no. 6 (2021): 4644-4669. https://doi.org/10.1021/acs.energyfuels.0c04112

[15] Singh, Akhilendra Pratap, Dhananjay Kumar, and Avinash Kumar Agarwal. "Introduction to alternative fuels and advanced combustion techniques as sustainable solutions for internal combustion engines." In *Alternative Fuels and Advanced Combustion Techniques as Sustainable Solutions for Internal Combustion Engines*, pp. 3-7. Singapore: Springer Singapore, 2021. https://doi.org/10.1007/978-981-16-1513-9_1

[16] Bielaczyc, Piotr, Joseph Woodburn, Andrzej Szczotka, and Piotr Pajdowski. "The impact of alternative fuels on fuel consumption and exhaust emissions of greenhouse gases from vehicles featuring SI engines." *Energy Procedia* 66 (2015): 21-24. https://doi.org/10.1016/j.egypro.2015.02.011

[17] Bae, Choongsik, and Jaeheun Kim. "Alternative fuels for internal combustion engines." *Proceedings of the Combustion Institute* 36, no. 3 (2017): 3389-3413. https://doi.org/10.1016/j.proci.2016.09.009

[18] Chen, Hao, Jingjing He, and Xianglin Zhong. "Engine combustion and emission fuelled with natural gas: a review." *Journal of the Energy Institute* 92, no. 4 (2019): 1123-1136. https://doi.org/10.1016/j.joei.2018.06.005

[19] Zhang, Qiang, Zhenguo Li, Zhangning Wei, Menghan Li, and Xuelong Zheng. "Experiment investigation on the emission characteristics of a stoichiometric natural gas engine operating with different reference fuels." *Fuel* 269 (2020): 117449. https://doi.org/10.1016/j.fuel.2020.117449

[20] Kim, Seonyeob, Cheolwoong Park, Hyungjoon Jang, Changgi Kim, and Yongrae Kim. "Effect of boosting on a

performance and emissions in a port fuel injection natural gas engine with variable intake and exhaust valve timing." *Energy Reports* 7 (2021): 4941-4950. https://doi.org/10.1016/j.egyr.2021.07.073

[21] Thangavelu, Saravana Kannan, Abu Saleh Ahmed, and Farid Nasir Ani. "Review on bioethanol as alternative fuel for spark ignition engines." *Renewable and Sustainable Energy Reviews* 56 (2016): 820-835. https://doi.org/10.1016/j.rser.2015.11.089

[22] Chen, Yisong, Jinqiu Ma, Bin Han, Peng Zhang, Haining Hua, Hao Chen, and Xin Su. "Emissions of automobiles fueled with alternative fuels based on engine technology: A review." *Journal of Traffic and Transportation Engineering (English Edition)* 5, no. 4 (2018): 318-334. https://doi.org/10.1016/j.jtte.2018.05.001

[23] Shang, Zhen, Xiumin Yu, Lei Ren, Guowu Wei, Guanting Li, Decheng Li, and Yinan Li. "Comparative study on effects of injection mode on combustion and emission characteristics of a combined injection n-butanol/gasoline SI engine with hydrogen direct injection." *Energy* 213 (2020): 118903. https://doi.org/10.1016/j.energy.2020.118903

[24] Appavu, Prabhu, Venkata Ramanan M., and Harish Venu. "Quaternary blends of diesel/biodiesel/vegetable oil/pentanol as a potential alternative feedstock for existing unmodified diesel engine: Performance, combustion and emission characteristics." *Energy* 186 (2019): 115856. https://doi.org/10.1016/j.energy.2019.115856

[25] Hancsók, Jenő. "Fuels For Internal Combustion Engines." *Kirk-Othmer Encyclopedia of Chemical Technology* (2016): 1-19. https://doi.org/10.1002/0471238961.koe00016

[26] Hua, Yang. "Research progress of higher alcohols as alternative fuels for compression ignition engines." *Fuel* 357 (2024): 129749. https://doi.org/10.1016/j.fuel.2023.129749

[27] Bakar, Rosli Abu, K. Kadirgama, K. V. Sharma, M. M. Rahman, and Semin. *Application of Natural Gas for Internal Combustion Engines*. INTECH Open Access Publisher, 2012.

[28] Li, Yuqiang, Karthik Nithyanandan, Timothy H. Lee, Robert Michael Donahue, Yilu Lin, Chia-Fon Lee, and Shengming Liao. "Effect of water-containing acetone-butanol-ethanol gasoline blends on combustion, performance, and emissions characteristics of a spark-ignition engine." *Energy Conversion and Management* 117 (2016): 21-30. https://doi.org/10.1016/j.enconman.2016.02.083

[29] Mandal, Adhirath, Haengmuk Cho, and Bhupendra Singh Chauhan. "ANN prediction of performance and emissions of CI engine using biogas flow variation." *Energies* 14, no. 10 (2021): 2910. https://doi.org/10.3390/en14102910

[30] Abu-Zaid, Mahmoud, Omar Badran, and J. Yamin. "Effect of methanol addition on the performance of spark ignition engines." *Energy & Fuels* 18, no. 2 (2004): 312-315. https://doi.org/10.1021/ef030103d

[31] Raza, Ali, Hassan Mehboob, Sajjad Miran, Waseem Arif, and Syed Farukh Javaid Rizvi. "Investigation on the characteristics of biodiesel droplets in the engine cylinder." *Energies* 13, no. 14 (2020): 3637. https://doi.org/10.3390/en13143637

[32] Martins, Jorge, and F. P. Brito. "Alternative fuels for internal combustion engines." *Energies* 13, no. 16 (2020): 4086. https://doi.org/10.3390/en13164086

[33] Sangeeta, Sangeeta, Sudheshna Moka, Maneesha Pande, Monika Rani, Ruchi Gakhar, Madhur Sharma, Jyoti Rani, and Ashok N. Bhaskarwar. "Alternative fuels: an overview of current trends and scope for future." *Renewable and Sustainable Energy Reviews* 32 (2014): 697-712. https://doi.org/10.1016/j.rser.2014.01.023

[34] Liang, Yufan. "A Review of the Effect of Compressed Natural Gas (CNG) on Combustion and Emission Performance of Internal Combustion Engines." *Trends in Renewable Energy* 8, no. 2 (2022): 119-129. https://doi.org/10.17737/tre.2022.8.2.00144

[35] Duan, Xiongbo, Banglin Deng, Yiqun Liu, Yangyang Li, and Jingping Liu. "Experimental study the impacts of the key operating and design parameters on the cycle-to-cycle variations of the natural gas SI engine." *Fuel* 290 (2021): 119976. https://doi.org/10.1016/j.fuel.2020.119976

[36] Kar, Tanmay, Zhenbiao Zhou, Michael Brear, Yi Yang, Maziar Khosravi, and Joshua Lacey. "A comparative study of directly injected, spark ignition engine performance and emissions with natural gas, gasoline and charge dilution." *Fuel* 304 (2021): 121438. https://doi.org/10.1016/j.fuel.2021.121438

[37] Chen, Zhanming, Tiancong Zhang, Xiaochen Wang, Hao Chen, Limin Geng, and Teng Zhang. "A comparative study of combustion performance and emissions of dual-fuel engines fueled with natural gas/methanol and natural gas/gasoline." *Energy* 237 (2021): 121586. https://doi.org/10.1016/j.energy.2021.121586

[38] Masum, B. M., H. H. Masjuki, M. A. Kalam, IM Rizwanul Fattah, S. M. Palash, and M. J. Abedin. "Effect of ethanol-gasoline blend on NOx emission in SI engine." *Renewable and Sustainable Energy Reviews* 24 (2013): 209-222. https://doi.org/10.1016/j.rser.2013.03.046

[39] Eyidogan, Muharrem, Ahmet Necati Ozsezen, Mustafa Canakci, and Ali Turkcan. "Impact of alcohol-gasoline fuel blends on the performance and combustion characteristics of an SI engine." *Fuel* 89, no. 10 (2010): 2713-2720. https://doi.org/10.1016/j.fuel.2010.01.032

[40] Masum, B. M., Haji Hassan Masjuki, M. A. Kalam, SMea Palash, and M. Habibullah. "Effect of alcohol-gasoline blends optimization on fuel properties, performance and emissions of a SI engine." *Journal of Cleaner Production* 86 (2015): 230-237. https://doi.org/10.1016/j.jclepro.2014.08.032

[41] Geo, V. Edwin, D. Jesu Godwin, Shanmugam Thiyagarajan, C. G. Saravanan, and Fethi Aloui. "Effect of higher and lower order alcohol blending with gasoline on performance, emission and combustion characteristics of SI engine." *Fuel* 256 (2019): 115806. https://doi.org/10.1016/j.fuel.2019.115806

[42] Yusoff, Mohd Nur Ashraf Mohd, Nurin Wahidah Mohd Zulkifli, Haji Hassan Masjuki, M. H. Harith, A. Z. Syahir, L. S. Khuong, Muhammad Syarifuddin Mohamed Zaharin, and Abdullah Alabdulkarem. "Comparative assessment of ethanol and isobutanol addition in gasoline on engine performance and exhaust emissions." *Journal of Cleaner Production* 190 (2018): 483-495. https://doi.org/10.1016/j.jclepro.2018.04.183

[43] Elfasakhany, Ashraf, and Abdel-Fattah Mahrous. "Performance and emissions assessment of n-butanol-methanol-gasoline blends as a fuel in spark-ignition engines." *Alexandria Engineering Journal* 55, no. 3 (2016): 3015-3024. https://doi.org/10.1016/j.aej.2016.05.016

[44] Yusoff, M. N. A. M., Nurin Wahidah Mohd Zulkifli, Haji Hassan Masjuki, M. H. Harith, A. Z. Syahir, Md Abul Kalam, M. F. Mansor, A. Azham, and L. S. Khuong. "Performance and emission characteristics of a spark ignition engine fuelled with butanol isomer-gasoline blends." *Transportation Research Part D: Transport and Environment* 57 (2017): 23-38. https://doi.org/10.1016/j.trd.2017.09.004

[45] Li, Xiao-Sen, Chun-Gang Xu, Yu Zhang, Xu-Ke Ruan, Gang Li, and Yi Wang. "Investigation into gas production from natural gas hydrate: A review." *Applied Energy* 172 (2016): 286-322. https://doi.org/10.1016/j.apenergy.2016.03.101

[46] Muniandy, Sumitra, Syuhaida Ismail, and Md Ezamudin Said. "Revenue/cost production sharing contract (psc) fiscal regime on marginal gas fields in Malaysia: Case study." *Progress in Energy and Environment* 26 (2023): 11-18. https://doi.org/10.37934/progee.26.1.1118

[47] Kakaee, Amir-Hasan, Amin Paykani, and Mostafa Ghajar. "The influence of fuel composition on the combustion and emission characteristics of natural gas fueled engines." *Renewable and Sustainable Energy Reviews* 38 (2014): 64-78. https://doi.org/10.1016/j.rser.2014.05.080

[48] Sagar, S. M. V., and Avinash Kumar Agarwal. "Knocking behavior and emission characteristics of a port fuel injected hydrogen enriched compressed natural gas fueled spark ignition engine." *Applied Thermal Engineering* 141 (2018): 42-50. https://doi.org/10.1016/j.applthermaleng.2018.05.102

[49] Rimkus, Alfredas, Tadas Vipartas, Donatas Kriaučiūnas, Jonas Matijošius, and Tadas Ragauskas. "The effect of intake valve timing on spark-ignition engine performances fueled by natural gas at low power." *Energies* 15, no. 2 (2022): 398. https://doi.org/10.3390/en15020398

[50] Singh, Eshan, Kai Morganti, and Robert Dibble. "Dual-fuel operation of gasoline and natural gas in a turbocharged engine." *Fuel* 237 (2019): 694-706. https://doi.org/10.1016/j.fuel.2018.09.158

[51] Reyes, Miriam, Andrés Melgar, Ana Pérez, and Blanca Giménez. "Study of the cycle-to-cycle variations of an internal combustion engine fuelled with natural gas/hydrogen blends from the diagnosis of combustion pressure." *International Journal of Hydrogen Energy* 38, no. 35 (2013): 15477-15487. https://doi.org/10.1016/j.ijhydene.2013.09.071

[52] Guido, Chiara, Pierpaolo Napolitano, Salvatore Alfuso, Corrado Corsetti, and Carlo Beatrice. "How engine design improvement impacts on particle emissions from an HD SI natural gas engine." *Energy* 231 (2021): 120748. https://doi.org/10.1016/j.energy.2021.120748

[53] Tian, Jiangping, Zechuan Cui, Zhongyong Ren, Hua Tian, and Wuqiang Long. "Experimental study on jet ignition and combustion processes of natural gas." *Fuel* 262 (2020): 116467. https://doi.org/10.1016/j.fuel.2019.116467

[54] Algayyim, Sattar Jabbar Murad, Khalid Saleh, Andrew P. Wandel, Islam Md Rizwanul Fattah, Talal Yusaf, and Hayder A. Alrazen. "Influence of natural gas and hydrogen properties on internal combustion engine performance, combustion, and emissions: A review." *Fuel* 362 (2024): 130844. https://doi.org/10.1016/j.fuel.2023.130844

[55] Chen, Lin, Haiqiao Wei, Ren Zhang, Jiaying Pan, Lei Zhou, and Changwen Liu. "Effects of late injection on lean combustion characteristics of methane in a high compression ratio optical engine." *Fuel* 255 (2019): 115718. https://doi.org/10.1016/j.fuel.2019.115718

[56] Zhang, Qiang, Yubo Yang, Demin Jia, and Menghan Li. "Knocking characteristics of a high pressure direct injection natural gas engine operating in stratified combustion mode." *Open Physics* 19, no. 1 (2021): 534-538. https://doi.org/10.1515/phys-2021-0064

[57] Sajan, Joseph. "CFD simulation of spark ignition engine with natural gas at varying compression ratio." In *AIP Conference Proceedings*, vol. 2317, no. 1. AIP Publishing, 2021. https://doi.org/10.1063/5.0036133

[58] Gharehghani, A., R. Hosseini, M. Mirsalim, and Talal F. Yusaf. "A comparative study on the first and second law analysis and performance characteristics of a spark ignition engine using either natural gas or gasoline." *Fuel* 158 (2015): 488-493. https://doi.org/10.1016/j.fuel.2015.05.067

[59] Duan, Xiongbo, Yiqun Liu, Ming-Chia Lai, Genmiao Guo, Jingping Liu, Zheng Chen, and Banglin Deng. "Effects of natural gas composition and compression ratio on the thermodynamic and combustion characteristics of a heavy-duty lean-burn SI engine fueled with liquefied natural gas." *Fuel* 254 (2019): 115733.

https://doi.org/10.1016/j.fuel.2019.115733

[60] Li, Yin, Jian Xue, Joshua Peppers, Norman Y. Kado, Christoph FA Vogel, Christopher P. Alaimo, Peter G. Green et al. "Chemical and toxicological properties of emissions from a Light-Duty compressed natural gas vehicle fueled with renewable natural gas." *Environmental Science & Technology* 55, no. 5 (2021): 2820-2830. https://doi.org/10.1021/acs.est.0c04962

[61] Melaika, Mindaugas, Gilles Herbillon, and Petter Dahlander. "Spark ignition engine performance, standard emissions and particulates using GDI, PFI-CNG and DI-CNG systems." *Fuel* 293 (2021): 120454. https://doi.org/10.1016/j.fuel.2021.120454

[62] Sun, Ping, Huamei Zhu, Song Yang, Wei Dong, Xiumin Yu, and Zhihao Fu. "Combustion and emission characteristics of CNG/gasoline DFSI engine with CNG direct injection." *Fuel* 359 (2024): 130537. https://doi.org/10.1016/j.fuel.2023.130537

[63] Tahir, Musthafah Mohd, M. S. Ali, M. A. Salim, Rosli A. Bakar, A. M. Fudhail, M. Z. Hassan, and MS Abdul Muhaimin. "Performance analysis of a spark ignition engine using compressed natural gas (CNG) as fuel." *Energy Procedia* 68 (2015): 355-362. https://doi.org/10.1016/j.egypro.2015.03.266

[64] Sahoo, Sridhar, and Dhananjay Kumar Srivastava. "Quantitative and qualitative analysis of thermodynamic process of a bi-fuel compressed natural gas spark ignition engine." *Environmental Progress & Sustainable Energy* 40, no. 4 (2021): e13583. https://doi.org/10.1002/ep.13583

[65] da Costa, Roberto Berlini Rodrigues, Juan J. Hernández, Alysson Fernandes Teixeira, Nilton Antonio Diniz Netto, Ramón Molina Valle, Vinícius Rückert Roso, and Christian JR Coronado. "Combustion, performance and emission analysis of a natural gas-hydrous ethanol dual-fuel spark ignition engine with internal exhaust gas recirculation." *Energy Conversion and Management* 195 (2019): 1187-1198. https://doi.org/10.1016/j.enconman.2019.05.094

[66] Kar, Tanmay, Zhenbiao Zhou, Michael Brear, Yi Yang, Maziar Khosravi, and Joshua Lacey. "A comparative study of directly injected, spark ignition engine performance and emissions with natural gas, gasoline and charge dilution." *Fuel* 304 (2021): 121438. https://doi.org/10.1016/j.fuel.2021.121438

[67] Duc, Khanh Nguyen, Vinh Nguyen Duy, Long Hoang-Dinh, Thanh Nguyen Viet, and Tuan Le-Anh. "Performance and emission characteristics of a port fuel injected, spark ignition engine fueled by compressed natural gas." *Sustainable Energy Technologies and Assessments* 31 (2019): 383-389. https://doi.org/10.1016/j.seta.2018.12.018

[68] Seboldt, Dimitri, David Lejsek, and Michael Bargende. "Injection strategies for low HC raw emissions in SI engines with CNG direct injection." *Automotive and Engine Technology* 1 (2016): 81-91. https://doi.org/10.1007/s41104-016-0002-4

[69] Patel, Rajesh, and Pragnesh Brahmbhatt. "Performance characteristics comparison of CNG port and CNG direct injection in spark ignition engine." *European Journal of Sustainable Development Research* 2, no. 2 (2018): 26. https://doi.org/10.20897/ejosdr/82058

[70] El-Sharkawy, Mohamed R., Mina BR Abaskharon, Ali M. Abd-El-Tawwab, and Fawzy MH Ezzat. "Effect of Static Spark Timing on the Performance and Emissions of a Spark Ignition Engine Using CNG." In *IOP Conference Series: Materials Science and Engineering*, vol. 518, no. 3, p. 032062. IOP Publishing, 2019. https://doi.org/10.1088/1757-899X/518/3/032062

[71] Usman, Muhammad, and Nasir Hayat. "Use of CNG and Hi-octane gasoline in SI engine: a comparative study of performance, emission, and lubrication oil deterioration." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 45, no. 4 (2023): 10983-10997. https://doi.org/10.1080/15567036.2019.1683098

[72] Yontar, Ahmet Alper, and Yahya Doğu. "Investigation of the effects of gasoline and CNG fuels on a dual sequential ignition engine at low and high load conditions." *Fuel* 232 (2018): 114-123. https://doi.org/10.1016/j.fuel.2018.05.156

[73] Nor Hisham, M. M., M. M. Edilan, M. A. Bakar, and S. O. Wasiu. "A study on the Viability of Dedicated Compressed Natural Gas System for Spark Ignition Engine." *Science & Engineering Technology National Conference* 2015 (2015).

[74] Le, Anh Tuan, Dang Quoc Tran, Thanh Tam Tran, Anh Tuan Hoang, and Van Viet Pham. "Performance and combustion characteristics of a retrofitted CNG engine under various piston-top shapes and compression ratios." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* (2020): 1-17. https://doi.org/10.1080/15567036.2020.1804016

[75] Yontar, Ahmet Alper, and Yahya Doğu. "Effects of equivalence ratio and CNG addition on engine performance and emissions in a dual sequential ignition engine." *International Journal of Engine Research* 21, no. 6 (2020): 1067-1082. https://doi.org/10.1177/1468087419834190

[76] Sahoo, Sridhar, and Dhananjay Kumar Srivastava. "Effect of compression ratio on engine knock, performance, combustion and emission characteristics of a bi-fuel CNG engine." *Energy* 233 (2021): 121144. https://doi.org/10.1016/j.energy.2021.121144

[77] Gowtham, R., A. Hakeem Meeran Bathusha, R. Sankara Ganapathy, K. Mohanraj, and N. Venkatasubramanian. "Performance and Emission Characterization of Adjustable Cylinder Head Type Variable Compression Ratio in Two-

Stroke SI Engine." In *IOP Conference Series: Materials Science and Engineering*, vol. 995, no. 1, p. 012005. IOP Publishing, 2020. https://doi.org/10.1088/1757-899X/995/1/012005

[78] Lather, Rohit Singh, and L. M. Das. "Performance and emission assessment of a multi-cylinder SI engine using CNG & HCNG as fuels." *International Journal of Hydrogen Energy* 44, no. 38 (2019): 21181-21192. https://doi.org/10.1016/j.ijhydene.2019.03.137

[79] Farooq, Muhammad Shahid, Ussama Ali, Muhammad Mubashir Farid, and Tanveer Mukhtar. "Experimental Investigation of Performance and Emissions of Spark Ignition Engine Fueled with Blends of HHO Gas with Gasoline and CNG." *International Journal of Thermal & Environmental Engineering* 18, no. 1 (2021): 27-34. https://doi.org/10.5383/ijtee.18.01.004

[80] Usman, Muhammad, Muhammad Wajid Saleem, Syed Saqib, Jamal Umer, Ahmad Naveed, and Zain Ul Hassan. "SI engine performance, lubricant oil deterioration, and emission: A comparison of liquid and gaseous fuel." *Advances in Mechanical Engineering* 12, no. 6 (2020): 1687814020930451. https://doi.org/10.1177/1687814020930451

[81] Aslam, M. U., H. H. Masjuki, M. A. Kalam, H. Abdesselam, T. M. I. Mahlia, and M. A. Amalina. "An experimental investigation of CNG as an alternative fuel for a retrofitted gasoline vehicle." *Fuel* 85, no. 5-6 (2006): 717-724. https://doi.org/10.1016/j.fuel.2005.09.004

[82] Park, Cheolwoong, Changgi Kim, Sangho Lee, Sunyoup Lee, and Janghee Lee. "Comparative evaluation of performance and emissions of CNG engine for heavy-duty vehicles fueled with various caloric natural gases." *Energy* 174 (2019): 1-9. https://doi.org/10.1016/j.energy.2019.02.120

[83] Lee, Jeongwoo, Cheolwoong Park, Jongwon Bae, Yongrae Kim, Sunyoup Lee, and Changgi Kim. "Comparison between gasoline direct injection and compressed natural gas port fuel injection under maximum load condition." *Energy* 197 (2020): 117173. https://doi.org/10.1016/j.energy.2020.117173

[84] Jahirul, Mohammad I., Haji Hassan Masjuki, Rahman Saidur, M. A. Kalam, M. H. Jayed, and M. A. Wazed. "Comparative engine performance and emission analysis of CNG and gasoline in a retrofitted car engine." *Applied Thermal Engineering* 30, no. 14-15 (2010): 2219-2226. https://doi.org/10.1016/j.applthermaleng.2010.05.037

[85] Payri, Raul, Ricardo Novella, Ibrahim Barbery, and Oscar Bori-Fabra. "Numerical and experimental evaluation of the passive pre-chamber concept for future CNG SI engines." *Applied Thermal Engineering* 230 (2023): 120754. https://doi.org/10.1016/j.applthermaleng.2023.120754

[86] Putrasari, Yanuandri, Achmad Praptijanto, Arifin Nur, Bambang Wahono, and Widodo Budi Santoso. "Evaluation of performance and emission of SI engine fuelled with CNG at low and high load condition." *Energy Procedia* 68 (2015): 147-156. https://doi.org/10.1016/j.egypro.2015.03.243

[87] Kakaee, Amirhasan, and Majid Karimi. "A comparative study on influence of natural gas composition on the performance of a CNG engine." *Mapta Journal of Mechanical and Industrial Engineering (MJMIE)* 2, no. 3 (2018): 9-18. https://doi.org/10.33544/mjmie.v2i3.76

[88] Ameri, Mohammad, Farzad Kiaahmadia, and Mansour Khanakib. "Comparative analysis of the performance of a dual-fuel internal combustion engine for CNG and gasoline fuels." *Journal of Power Technologies* 92, no. 4 (2012): 214-226.

[89] Ganesan, Nataraj, Bragadeshwaran Ashok, Dhinesh Balasubramanian, K. Anabayan, Krupakaran Radhakrishnan Lawrence, A. Tamilvanan, Duc Trong Nguyen Le et al. "Eco-friendly perspective of hydrogen fuel addition to diesel engine: An inclusive review of low-temperature combustion concepts." *International Journal of Hydrogen Energy* (2024).

[90] Hoekstra, Robert L., Peter Van Blarigan, and Neal Mulligan. *NOx Emissions and Efficiency of Hydrogen, Natural Gas, and Hydrogen/Natural Gas Blended Fuels*. No. 961103. SAE Technical Paper, 1996. https://doi.org/10.4271/961103

[91] Stępień, Zbigniew. "A comprehensive overview of hydrogen-fueled internal combustion engines: Achievements and future challenges." *Energies* 14, no. 20 (2021): 6504. https://doi.org/10.3390/en14206504

[92] Akal, Dinçer, Semiha Öztuna, and Mustafa Kemalettin Büyükakın. "A review of hydrogen usage in internal combustion engines (gasoline-Lpg-diesel) from combustion performance aspect." *International Journal of Hydrogen Energy* 45, no. 60 (2020): 35257-35268. https://doi.org/10.1016/j.ijhydene.2020.02.001

[93] Qu, Wenjing, Yuan Fang, Zixin Wang, Hongjie Sun, and Liyan Feng. "Optimization of injection system for a medium-speed four-stroke spark-ignition marine hydrogen engine." *International Journal of Hydrogen Energy* 47, no. 44 (2022): 19289-19297. https://doi.org/10.1016/j.ijhydene.2022.04.096

[94] Khan, Muhammad Imran, Tabassum Yasmin, and Abdul Shakoor. "Technical overview of compressed natural gas (CNG) as a transportation fuel." *Renewable and Sustainable Energy Reviews* 51 (2015): 785-797. https://doi.org/10.1016/j.rser.2015.06.053

[95] Mehra, Roopesh Kumar, Hao Duan, Romualdas Juknelevičius, Fanhua Ma, and Junyin Li. "Progress in hydrogen enriched compressed natural gas (HCNG) internal combustion engines-A comprehensive review." *Renewable and Sustainable Energy Reviews* 80 (2017): 1458-1498. https://doi.org/10.1016/j.rser.2017.05.061

[96] Alrazen, Hayder A., and K. A. Ahmad. "HCNG fueled spark-ignition (SI) engine with its effects on performance and

emissions." *Renewable and Sustainable Energy Reviews* 82 (2018): 324-342. https://doi.org/10.1016/j.rser.2017.09.035

[97] Sgaramella, Antonio, Lorenzo Mario Pastore, Gianluigi Lo Basso, Ali Mojtahed, and Livio de Santoli. "HCNG refuelling station to accelerate the transition towards a real hydrogen economy: A techno-economic analysis." *International Journal of Hydrogen Energy* 69 (2024): 1403-1416. https://doi.org/10.1016/j.ijhydene.2024.05.145

[98] Qadiri, Ufaith, D. Siva Krishna Reddy, Amjad Ali Pasha, and Mohammad Irfan Alam. "One-dimensional numerical investigation on multi-cylinder gasoline engine fueled by micro-emulsions, CNG, and hydrogen in dual fuel mode." *Chinese Journal of Aeronautics* 36, no. 5 (2023): 57-65. https://doi.org/10.1016/j.cja.2023.02.030

[99] De Simio, Luigi, Sabato Iannaccone, Chiara Guido, Pierpaolo Napolitano, and Armando Maiello. "Natural Gas/Hydrogen blends for heavy-duty spark ignition engines: Performance and emissions analysis." *International Journal of Hydrogen Energy* 50 (2024): 743-757. https://doi.org/10.1016/j.ijhydene.2023.06.194

[100] Singh, Sauhard, Sumit Mishra, Reji Mathai, A. K. Sehgal, and R. Suresh. "Comparative study of unregulated emissions on a heavy duty CNG engine using CNG & hydrogen blended CNG as fuels." *SAE International Journal of Engines* 9, no. 4 (2016): 2292-2300. https://doi.org/10.4271/2016-01-8090

[101] Duan, Xiongbo, Banglin Deng, Yiqun Liu, Shunzhang Zou, Jingping Liu, and Renhua Feng. "An experimental study the impact of the hydrogen enrichment on cycle-to-cycle variations of the large bore and lean burn natural gas spark-ignition engine." *Fuel* 282 (2020): 118868. https://doi.org/10.1016/j.fuel.2020.118868

[102] Prasad, Rajesh Kumar, Nirendra Mustafi, and Avinash Kumar Agarwal. "Effect of spark timing on laser ignition and spark ignition modes in a hydrogen enriched compressed natural gas fuelled engine." *Fuel* 276 (2020): 118071. https://doi.org/10.1016/j.fuel.2020.118071

[103] Prasad, Rajesh Kumar, and Avinash Kumar Agarwal. "Experimental evaluation of laser ignited hydrogen enriched compressed natural gas fueled supercharged engine." *Fuel* 289 (2021): 119788. https://doi.org/10.1016/j.fuel.2020.119788

[104] Leng, Xianyin, Haiqi Huang, Qiqi Ge, Zhixia He, Yanzhi Zhang, Qian Wang, Dongze He, and Wuqiang Long. "Effects of hydrogen enrichment on the combustion and emission characteristics of a turbulent jet ignited medium speed natural gas engine: A numerical study." *Fuel* 290 (2021): 119966. https://doi.org/10.1016/j.fuel.2020.119966

[105] Prasad, Rajesh Kumar, and Avinash Kumar Agarwal. "Effect of hydrogen enrichment of compressed natural gas on combustible limit and flame kernel evolution in a constant volume combustion chamber using laser ignition." *Fuel* 302 (2021): 121112. https://doi.org/10.1016/j.fuel.2021.121112

[106] Hao, Duan, Roopesh Kumar Mehra, Sijie Luo, Zhibin Nie, Xiaohui Ren, and Ma Fanhua. "Experimental study of hydrogen enriched compressed natural gas (HCNG) engine and application of support vector machine (SVM) on prediction of engine performance at specific condition." *International Journal of Hydrogen Energy* 45, no. 8 (2020): 5309-5325. https://doi.org/10.1016/j.ijhydene.2019.04.039

[107] Zhang, Ren, Lin Chen, Haiqiao Wei, Jiaying Pan, Jinguang Li, Penghui Yang, and Rui Chen. "Optical study on the effects of the hydrogen injection timing on lean combustion characteristics using a natural gas/hydrogen dual-fuel injected spark-ignition engine." *International Journal of Hydrogen Energy* 46, no. 39 (2021): 20777-20789. https://doi.org/10.1016/j.ijhydene.2021.03.171

[108] Zareei, Javad, Abbas Rohani, Farhad Mazari, and Maria Vladimirovna Mikkhailova. "Numerical investigation of the effect of two-step injection (direct and port injection) of hydrogen blending and natural gas on engine performance and exhaust gas emissions." *Energy* 231 (2021): 120957. https://doi.org/10.1016/j.energy.2021.120957

[109] Prasad, Rajesh Kumar, and Avinash Kumar Agarwal. "Development and comparative experimental investigations of laser plasma and spark plasma ignited hydrogen enriched compressed natural gas fueled engine." *Energy* 216 (2021): 119282. https://doi.org/10.1016/j.energy.2020.119282

[110] Park, Bum Youl, Ki-Hyung Lee, and Jungsoo Park. "Conceptual approach on feasible hydrogen contents for retrofit of CNG to HCNG under heavy-duty spark ignition engine at low-to-middle speed ranges." *Energies* 13, no. 15 (2020): 3861. https://doi.org/10.3390/en13153861

[111] Barbu, Marius Cătălin, Adrian Birtaş, and Radu Chiriac. "On the improvement of performance and pollutant emissions of a spark ignition engine fuelled by compressed natural gas and hydrogen." *Energy Reports* 8 (2022): 978-991. https://doi.org/10.1016/j.egyr.2022.07.136

[112] Duan, Xiongbo, Yiqun Liu, Jingping Liu, Ming-Chia Lai, Marcis Jansons, Genmiao Guo, Shiheng Zhang, and Qijun Tang. "Experimental and numerical investigation of the effects of low-pressure, high-pressure and internal EGR configurations on the performance, combustion and emission characteristics in a hydrogen-enriched heavy-duty lean-burn natural gas SI engine." *Energy Conversion and Management* 195 (2019): 1319-1333. https://doi.org/10.1016/j.enconman.2019.05.059

[113] Luo, Sijie, Fanhua Ma, Roopesh Kumar Mehra, and Zuohua Huang. "Deep insights of HCNG engine research in China." *Fuel* 263 (2020): 116612. https://doi.org/10.1016/j.fuel.2019.116612

[114] Hora, Tadveer Singh, and Avinash Kumar Agarwal. "Experimental study of the composition of hydrogen enriched

compressed natural gas on engine performance, combustion and emission characteristics." *Fuel* 160 (2015): 470-478. https://doi.org/10.1016/j.fuel.2015.07.078

[115] Li, Gesheng, Yangxiang Long, Zunhua Zhang, Junjie Liang, Xiaowu Zhang, Xintang Zhang, and Zhongjun Wang. "Performance and emissions characteristics of a lean-burn marine natural gas engine with the addition of hydrogen-rich reformate." *International Journal of Hydrogen Energy* 44, no. 59 (2019): 31544-31556. https://doi.org/10.1016/j.ijhydene.2019.10.007

[116] Sopena, C., P. M. Diéguez, D. Sáinz, J. C. Urroz, E. Guelbenzu, and L. M. Gandía. "Conversion of a commercial spark ignition engine to run on hydrogen: Performance comparison using hydrogen and gasoline." *International Journal of Hydrogen Energy* 35, no. 3 (2010): 1420-1429. https://doi.org/10.1016/j.ijhydene.2009.11.090

[117] Wasiu, Saheed, Rashid Abdul Aziz, and Puteri Megat. "Brake Specific Energy Consumption (BSEC) and Emission Characteristics of the Direct Injection Spark Ignition Engine Fuelled by Hydrogen Enriched Compressed Natural Gas at Various Air-Fuel Ratios." *International Journal of Applied Engineering Research* 13, no. 1 (2018): 677-683.

[118] Mehra, Roopesh Kumar, Hao Duan, Sijie Luo, Anas Rao, and Fanhua Ma. "Experimental and artificial neural network (ANN) study of hydrogen enriched compressed natural gas (HCNG) engine under various ignition timings and excess air ratios." *Applied Energy* 228 (2018): 736-754. https://doi.org/10.1016/j.apenergy.2018.06.085

[119] Yu, Xiumin, Guanting Li, Yaodong Du, Zezhou Guo, Zhen Shang, Fengshuo He, Qingxu Shen, Decheng Li, and Yinan Li. "A comparative study on effects of homogeneous or stratified hydrogen on combustion and emissions of a gasoline/hydrogen SI engine." *International Journal of Hydrogen Energy* 44, no. 47 (2019): 25974-25984. https://doi.org/10.1016/j.ijhydene.2019.08.029

[120] Pandey, Vivek, Suresh Guluwadi, and Gezahegn Habtamu Tafesse. "Performance and emission study of low HCNG fuel blend in SI engine with fixed ignition timing." *Cogent Engineering* 9, no. 1 (2022): 2010925. https://doi.org/10.1080/23311916.2021.2010925

[121] Topgül, Tolga, Can Cınar, and Onur Ozdemır. "The variations of the exhaust emissions at low ambient temperature for E10 and M10 fueled SI engine." *Isı Bilimi ve Tekniği Dergisi* 41, no. 2 (2021): 227-237. https://doi.org/10.47480/isibted.1025931

[122] Wang, Xin, Yunshan Ge, Linlin Liu, Zihang Peng, Lijun Hao, Hang Yin, Yan Ding, and Junfang Wang. "Evaluation on toxic reduction and fuel economy of a gasoline direct injection-(GDI-) powered passenger car fueled with methanol-gasoline blends with various substitution ratios." *Applied Energy* 157 (2015): 134-143. https://doi.org/10.1016/j.apenergy.2015.08.023

[123] Hua, Yang, Fushui Liu, Han Wu, Chia-Fon Lee, and Yikai Li. "Effects of alcohol addition to traditional fuels on soot formation: A review." *International Journal of Engine Research* 22, no. 5 (2021): 1395-1420. https://doi.org/10.1177/1468087420910886

[124] Göktaş, Meltem, Mustafa Kemal Balki, Cenk Sayin, and Mustafa Canakci. "An evaluation of the use of alcohol fuels in SI engines in terms of performance, emission and combustion characteristics: A review." *Fuel* 286 (2021): 119425. https://doi.org/10.1016/j.fuel.2020.119425

[125] Huang, Yuhan, Nic C. Surawski, Yuan Zhuang, John L. Zhou, and Guang Hong. "Dual injection: An effective and efficient technology to use renewable fuels in spark ignition engines." *Renewable and Sustainable Energy Reviews* 143 (2021): 110921. https://doi.org/10.1016/j.rser.2021.110921

[126] Koç, Mustafa, Yakup Sekmen, Tolga Topgül, and Hüseyin Serdar Yücesu. "The effects of ethanol-unleaded gasoline blends on engine performance and exhaust emissions in a spark-ignition engine." *Renewable Energy* 34, no. 10 (2009): 2101-2106. https://doi.org/10.1016/j.renene.2009.01.018

[127] Kroyan, Yuri, Michal Wojcieszyk, Ossi Kaario, Martti Larmi, and Kai Zenger. "Modeling the end-use performance of alternative fuels in light-duty vehicles." *Energy* 205 (2020): 117854. https://doi.org/10.1016/j.energy.2020.117854

[128] Kawakami, Tadashige. "A study of emission reduction by using alcohol blend fuel for small diesel engine." *Journal of KONES* 21, no. 1 (2014): 125-130. https://doi.org/10.5604/12314005.1134061

[129] Ali, Eman N., and M. Z. Jamaludin. "Possibility of producing ethanol from Moringa Oleifera pod husk." *Journal of Advanced Research Design* 5, no. 1 (2015): 1-9.

[130] Quintero, J. A., M. I. Montoya, Ó J. Sánchez, O. H. Giraldo, and C. A. Cardona. "Fuel ethanol production from sugarcane and corn: comparative analysis for a Colombian case." *Energy* 33, no. 3 (2008): 385-399. https://doi.org/10.1016/j.energy.2007.10.001

[131] Senatore, Alessandro, Francesco Dalena, Alessia Sola, Alessia Marino, Valeria Valletta, and Angelo Basile. "First-generation feedstock for bioenergy production." In *Second and Third Generation of Feedstocks*, pp. 35-57. Elsevier, 2019. https://doi.org/10.1016/B978-0-12-815162-4.00002-1

[132] Senatore, Alessandro, Francesco Dalena, and Angelo Basile. "Novel bioethanol production processes and purification technology using membranes." In *Studies in Surface Science and Catalysis*, vol. 179, pp. 359-384. Elsevier, 2020. https://doi.org/10.1016/B978-0-444-64337-7.00019-7

[133] Vasić, Katja, Željko Knez, and Maja Leitgeb. "Bioethanol production by enzymatic hydrolysis from different

lignocellulosic sources." *Molecules* 26, no. 3 (2021): 753. https://doi.org/10.3390/molecules26030753

[134] Stein, Robert A., James E. Anderson, and Timothy J. Wallington. "An overview of the effects of ethanol-gasoline blends on SI engine performance, fuel efficiency, and emissions." *SAE International Journal of Engines* 6, no. 1 (2013): 470-487. https://doi.org/10.4271/2013-01-1635

[135] Anderson, J. E., D. M. DiCicco, J. M. Ginder, U. Kramer, T. G. Leone, H. E. Raney-Pablo, and T. J. Wallington. "High octane number ethanol-gasoline blends: Quantifying the potential benefits in the United States." *Fuel* 97 (2012): 585-594. https://doi.org/10.1016/j.fuel.2012.03.017

[136] Nigam, Poonam Singh, and Anoop Singh. "Production of liquid biofuels from renewable resources." *Progress in Energy and Combustion Science* 37, no. 1 (2011): 52-68. https://doi.org/10.1016/j.pecs.2010.01.003

[137] Zabed, Herman, J. N. Sahu, A. Suely, A. N. Boyce, and G. Faruq. "Bioethanol production from renewable sources: Current perspectives and technological progress." *Renewable and Sustainable Energy Reviews* 71 (2017): 475-501. https://doi.org/10.1016/j.rser.2016.12.076

[138] Balat, Mustafa, Havva Balat, and Cahide Öz. "Progress in bioethanol processing." *Progress in Energy and Combustion Science* 34, no. 5 (2008): 551-573. https://doi.org/10.1016/j.pecs.2007.11.001

[139] Hashim, Rushanim, Sarah Cooper, Nurul Azita Salleh, and Mohd Nasrun Mohd Nawi. "The influence of regulatory pressure in shaping construction firms' decision to adopt green innovation." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 28, no. 2 (2022): 301-310. https://doi.org/10.37934/araset.28.2.301310

[140] M'hamed, Beriache, Moustefa Hadj Henni, Leila Mokhtar Saïdia, Bassam Gamal Nasser Muthanna, Ahmad Tajuddin Mohamad, and Nor Azwadi Che Sidik. "Experimental Evaluation of the Performance of a Diesel Engine Feeding with Ethanol/Diesel and Methanol/Diesel." *Journal of Advanced Research in Experimental Fluid Mechanics and Heat Transfer* 15, no. 1 (2024): 14-27. https://doi.org/10.37934/arefmht.15.1.1427

[141] Hofny, Mohamed S., Nouby M. Ghazaly, Ahmed N. Shmroukh, and Mostafa Abouelsoud. "Comparative Study of ANN and SVM Model Network Performance for Predicting Brake Power in SI Engines Using E15 Fuel." *International Journal of Robotics and Control Systems* 4, no. 3 (2024): 979-999.

[142] Lin, Yan, and Shuzo Tanaka. "Ethanol fermentation from biomass resources: current state and prospects." *Applied Microbiology and Biotechnology* 69 (2006): 627-642. https://doi.org/10.1007/s00253-005-0229-x

[143] Jee, Jap Haw, and Lian See Tan. "Investigation on the potential of bioethanol synthesis from honeydew melon rind." *Progress in Energy and Environment* 16 (2021): 45-58.

[144] Eggeman, Tim, and Richard T. Elander. "Process and economic analysis of pretreatment technologies." *Bioresource Technology* 96, no. 18 (2005): 2019-2025. https://doi.org/10.1016/j.biortech.2005.01.017

[145] Kunwer, Ram, Subrahmanya Ranjit Pasupuleti, Swapnil Sureshchandra Bhurat, Santhosh Kumar Gugulothu, and Devandra Singh. "Effect of ethanol-gasoline blend on spark ignition engine: A mini review." *Materials Today: Proceedings* 69 (2022): 564-568. https://doi.org/10.1016/j.matpr.2022.09.320

[146] Agarwal, Avinash Kumar. "Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines." *Progress in Energy and Combustion Science* 33, no. 3 (2007): 233-271. https://doi.org/10.1016/j.pecs.2006.08.003

[147] Fan, Yadong, Zhe Sun, Qifan Gu, Qinglin Xu, Xuesong Li, and Min Xu. "Combustion improved by using flash boiling sprays in an ethanol-gasoline optical engine under cold operating conditions." *Energy & Fuels* 35, no. 12 (2021): 10134-10145. https://doi.org/10.1021/acs.energyfuels.1c00739

[148] Jamrozik, Arkadiusz, Wojciech Tutak, Michał Pyrc, and Michał Sobiepański. "Effect of diesel-biodiesel-ethanol blend on combustion, performance, and emissions characteristics on a direct injection diesel engine." *Thermal Science* 21, no. 1 Part B (2017): 591-604. https://doi.org/10.2298/TSCI160913275J

[149] Tutak, Wojciech, Arkadiusz Jamrozik, and Renata Gnatowska. "Combustion of different reactivity fuel mixture in a dual fuel engine." *Thermal Science* 22, no. 3 (2018): 1285-1297. https://doi.org/10.2298/TSCI170606299T

[150] Wang, Yinan, Maji Luo, and Musaab O. El-Faroug. "The influence of hydrous ethanol gasoline on cycle-to-cycle variation of a spark ignition engine." *Thermal Science* 22, no. 3 (2018): 1373-1384. https://doi.org/10.2298/TSCI171221095W

[151] Salamanca, Maurin, Mauricio Velasquez, Fanor Mondragon, and Alexander Santamaria. "Variations of the soot precursors chemical composition induced by ethanol addition to fuel." *Energy & Fuels* 26, no. 11 (2012): 6602-6611. https://doi.org/10.1021/ef300926y

[152] Iodice, Paolo, Giuseppe Langella, and Amedeo Amoresano. "Ethanol in gasoline fuel blends: Effect on fuel consumption and engine out emissions of SI engines in cold operating conditions." *Applied Thermal Engineering* 130 (2018): 1081-1089. https://doi.org/10.1016/j.applthermaleng.2017.11.090

[153] Iodice, Paolo, and Massimo Cardone. "Ethanol/gasoline blends as alternative fuel in last generation spark-ignition engines: a review on CO and HC engine out emissions." *Energies* 14, no. 13 (2021): 4034. https://doi.org/10.3390/en14134034

[154] Parthasarathy, Prakash, and Sheeba K. Narayanan. "Effect of hydrothermal carbonization reaction parameters on."

Environmental Progress & Sustainable Energy 33, no. 3 (2014): 676-680. https://doi.org/10.1002/ep.11974

[155] Kumbhar, S. V., and S. A. Khot. "Experimental investigations of ethanol-gasoline blends on the performance, combustion, and emission characteristics of spark ignition engine spark ignition (SI) engine with partial addition of n-pentane." *Materials Today: Proceedings* 77 (2023): 647-653. https://doi.org/10.1016/j.matpr.2022.11.284

[156] Najafi, G., B. Ghobadian, T. Tavakoli, D. R. Buttsworth, T. F. Yusaf, and M. J. A. E. Faizollahnejad. "Performance and exhaust emissions of a gasoline engine with ethanol blended gasoline fuels using artificial neural network." *Applied Energy* 86, no. 5 (2009): 630-639. https://doi.org/10.1016/j.apenergy.2008.09.017

[157] Liu, Shang, Zhelong Lin, Hao Zhang, Qinhao Fan, Nuo Lei, and Zhi Wang. "Experimental study on combustion and emission characteristics of ethanol-gasoline blends in a high compression ratio SI engine." *Energy* 274 (2023): 127398. https://doi.org/10.1016/j.energy.2023.127398

[158] Kim, Youngkun, Woong Il Kim, Byounghyouk Min, Juhyeong Seo, and Kihyung Lee. "Experimental investigation of combustion characteristics of ethanol-gasoline blended fuel in a T-GDI engine." *Applied Thermal Engineering* 208 (2022): 118168. https://doi.org/10.1016/j.applthermaleng.2022.118168

[159] Rao, Ravinanath Narenthra, Arridina Susan Silitonga, Abd Halim Shamsuddin, Jassinnee Milano, Teuku Meurah Indra Riayatsyah, A. H. Sebayang, Taufiq Bin Nur, M. Sabri, M. R. Yulita, and R. W. Sembiring. "Effect of ethanol and gasoline blending on the performance of a stationary small single cylinder engine." *Arabian Journal for Science and Engineering* 45 (2020): 5793-5802. https://doi.org/10.1007/s13369-020-04567-7

[160] Al-Hasan, M. "Effect of ethanol-unleaded gasoline blends on engine performance and exhaust emission." *Energy Conversion and Management* 44, no. 9 (2003): 1547-1561. https://doi.org/10.1016/S0196-8904(02)00166-8

[161] Chaimanatsakun, Attaphon, Boonlue Sawatmongkhon, Sak Sittichompoo, and Kampanart Theinnoi. "Effects of reformed exhaust gas recirculation (REGR) of ethanol-gasoline fuel blends on the combustion and emissions of gasoline direct injection (GDI) engine." *Fuel* 355 (2024): 129506. https://doi.org/10.1016/j.fuel.2023.129506

[162] Mohammed, Mortadha K., Hyder H. Balla, Zaid Maan H. Al-Dulaimi, Zaid S. Kareem, and Mudhaffar S. Al-Zuhairy. "Effect of ethanol-gasoline blends on SI engine performance and emissions." *Case Studies in Thermal Engineering* 25 (2021): 100891. https://doi.org/10.1016/j.csite.2021.100891

[163] Sakthivel, P., K. A. Subramanian, and Reji Mathai. "Effects of different compression ratios and spark timings on performance and emissions of a two-wheeler with 30% ethanol-gasoline blend (E30)." *Fuel* 277 (2020): 118113. https://doi.org/10.1016/j.fuel.2020.118113

[164] Hosseini, Hossein, Alireza Hajialimohammadi, Iraj Jafari Gavzan, and Mohammad Ali Hajimousa. "Numerical and experimental investigation on the effect of using blended gasoline-ethanol fuel on the performance and the emissions of the bi-fuel Iranian national engine." *Fuel* 337 (2023): 127252. https://doi.org/10.1016/j.fuel.2022.127252

[165] Kumar, Venktesh, Shashi Kumar Jain, and Ankit Goyal. "Performance Analysis of Gasoline Engine with Different Ethanol Blends." *American Journal of Modern Energy* 9, no. 2 (2023): 36-41. https://doi.org/10.11648/j.ajme.20230902.12

[166] James, Precious Emesomi, Mohammed Moore Ojapah, Celestine Ebieto Celestine, Oghneruona Diemuodeke, Ofodu Joseph Chukwuka, and Nehemia Sabinus Alozie. "Effects of Load on Gaseous Emissions of Gasoline and Ethanol Blends in a Single Cylinder Production Engine." *International Journal of Advances in Engineering and Management (IJAEM)* 5, no. 3 (2023): 1877-1888.

[167] Verma, Atul, Navdeep Sharma Dugala, and Supreet Singh. "Experimental investigations on the performance of SI engine with Ethanol-Premium gasoline blends." *Materials Today: Proceedings* 48 (2022): 1224-1231. https://doi.org/10.1016/j.matpr.2021.08.255

[168] Tornatore, Cinzia, Luca Marchitto, Maria Antonietta Costagliola, and Gerardo Valentino. "Experimental comparative study on performance and emissions of e85 adopting different injection approaches in a turbocharged pfi si Engine." *Energies* 12, no. 8 (2019): 1555. https://doi.org/10.3390/en12081555

[169] Chandrasekar, K., S. Sudhakar, R. Rajappan, S. Senthil, and P. Balu. "Present developments and the reach of alternative fuel: A review." *Materials Today: Proceedings* 51 (2022): 74-83. https://doi.org/10.1016/j.matpr.2021.04.505

[170] Ebhota, Williams S., and Tien-Chien Jen. "Fossil fuels environmental challenges and the role of solar photovoltaic technology advances in fast tracking hybrid renewable energy system." *International Journal of Precision Engineering and Manufacturing-Green Technology* 7 (2020): 97-117. https://doi.org/10.1007/s40684-019-00101-9

[171] Reitz, Rolf D., H. Ogawa, R. Payri, T. Fansler, S. Kokjohn, Y. Moriyoshi, A. K. Agarwal et al. "IJER editorial: The future of the internal combustion engine." *International Journal of Engine Research* 21, no. 1 (2020): 3-10. https://doi.org/10.1177/1468087419877990

[172] Abas, Naeem, A. Kalair, and Nasrullah Khan. "Review of fossil fuels and future energy technologies." *Futures* 69 (2015): 31-49. https://doi.org/10.1016/j.futures.2015.03.003

[173] Azni, Muhammad Asyraf, Rasyikah Md Khalid, Umi Azmah Hasran, and Siti Kartom Kamarudin. "Review of the

effects of fossil fuels and the need for a hydrogen fuel cell policy in Malaysia." *Sustainability* 15, no. 5 (2023): 4033. https://doi.org/10.3390/su15054033

[174] Whitley, Shelagh, and Laurie Van der Burg. "Fossil fuel subsidy reform in sub-Saharan Africa: from rhetoric to reality." *New Climate Economy, London and Washington, DC* (2015).

[175] Armaroli, Nicola, and Vincenzo Balzani. "The future of energy supply: challenges and opportunities." *Angewandte Chemie International Edition* 46, no. 1-2 (2007): 52-66. https://doi.org/10.1002/anie.200602373

[176] Lahn, Glada, and Siân Bradley. "Left stranded? Extractives-led growth in a carbon-constrained world." *Research Paper, Energy, Environment and Resources Department* (2016).

[177] Dominković, Dominik Franjo, Ivan Bačeković, Allan Schrøder Pedersen, and Goran Krajačić. "The future of transportation in sustainable energy systems: Opportunities and barriers in a clean energy transition." *Renewable and Sustainable Energy Reviews* 82 (2018): 1823-1838. https://doi.org/10.1016/j.rser.2017.06.117

[178] Zou, Caineng, Qun Zhao, Guosheng Zhang, and Bo Xiong. "Energy revolution: From a fossil energy era to a new energy era." *Natural Gas Industry B* 3, no. 1 (2016): 1-11. https://doi.org/10.1016/j.ngib.2016.02.001

[179] Larcher, Dominique, and Jean-Marie Tarascon. "Towards greener and more sustainable batteries for electrical energy storage." *Nature Chemistry* 7, no. 1 (2015): 19-29. https://doi.org/10.1038/nchem.2085

[180] Backhouse, Maria, Fabricio Rodríguez, and Anne Tittor. "From a fossil towards a renewable energy regime in the Americas? Socio-ecological inequalities, contradictions and challenges for a global bioeconomy." *Bioeconomy & Inequalities* (2019).

[181] Gur, Turgut M. "Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage." *Energy & Environmental Science* 11, no. 10 (2018): 2696-2767. https://doi.org/10.1039/C8EE01419A