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Review article

Influence of natural gas and hydrogen properties on internal combustion engine performance, combustion, and emissions: A review

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ABSTRACT

This paper provides a comprehensive overview of the physical properties and applications of natural gas (NG) and hydrogen as fuels in internal combustion (IC) engines. The paper also meticulously examines the use of both NG and hydrogen as a fuel in vehicles, their production, physical characteristics, and combustion properties. It reviews the current experimental studies in the literature and investigates the results of using both fuels. It further covers the challenges associated with injectors, needle valves, lubrication, spark plugs, and safety requirements for both fuels. Finally, the challenges related to the storage, production, and safety of both fuels are also discussed. The literature review reveals that NG in spark ignition (SI) engines has a clear and direct positive impact on fuel economy and certain emissions, notably reducing CO_2 and non-methane hydrocarbons. However, its effect on other emissions, such as unburnt hydrocarbons (UHC), nitrogen oxides (NO_x), and carbon monoxide (CO), is less clear. NG, which is primarily methane, has a lower carbon-to-hydrogen ratio than diesel fuel, resulting in lower CO_2 emissions per unit of energy released. In contrast, hydrogen is particularly well-suited for use in gasoline engines due to its high self-ignition temperature. While increasing the hydrogen content of NG engines reduces torque and power output, higher hydrogen input results in reduced fuel consumption and the mitigation of toxic exhaust emissions. Due to its high ignition temperature, hydrogen is not inherently suitable for direct use in diesel engines, necessitating the exploration of alternative methods for hydrogen introduction into the cylinder. The literature review suggests that hydrogen in diesel engines has shown a reduction in specific exhaust emissions and fuel consumption and an increase in NO_x emissions. Overall, the paper provides a valuable and informative overview of the challenges and opportunities associated with using hydrogen and NG as fuels in IC engines. It highlights the need for further research and development to address the remaining challenges, such as the development of more efficient combustion chambers and the reduction of NO_x emissions.

1. Introduction

The increasing global demand for energy, rising energy costs, and growing environmental concerns have led to intensified research efforts to reduce fuel consumption and mitigate the concentration of harmful pollutants in exhaust emissions. This impetus has driven the exploration of alternative energy sources and fuels [1–6]. Moreover, the rapid depletion of conventional fossil fuels has further incentivized the development of engines that can use unconventional fuels. The negative environmental impact of fossil fuel combustion, especially in transportation, has highlighted the need to address these challenges urgently [7–13]. Environmental protection and the need to reduce fossil fuel emissions have become increasingly important global priorities [2,7,14,15].

To address the significant emissions from conventional fuel-based

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Nomenclature

ATR	Autothermal Reforming
BTE	Brake Thermal Efficiency
BP	Brake Power
BMEP	Brake Mean Effective Pressure
BHP	Biological Hydrogen Production
CI	Compression Ignition
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CCS	Carbon Capture and Storage
CAGR	Compound Annual Growth Rate
COV	Coefficient of Variation
CR	Compression Ratio
CNG	Compressed Natural Gas
DI	Direct Injection
DF	Dual Fuel
DI NG	Direct Injection Natural Gas
D	Diesel fuel
GIT	Gas Injection Timings
EHCC	Eccentric Hemispherical Combustion Chamber
EGR	Exhaust Gas Recirculation
EIA	Energy Information Administration's
FCEVs	Fuel Cell Electric Vehicles
IC	Internal Combustion
IEA	International Energy Agency
IMEP	Indicated Mean Effective Pressure
HRR	Heat Release Rate
GTL	Gas-To-Liquid
FCVs	Fuel Cell Vehicles
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
NG	Natural Gas
NOx	Nitrogen Oxides
PFI	Port Fuel Injection
POX	Partial Oxidation
PR	Pressure Ratios
PN	Nanoparticle
SR	Reforming
SI	Spark Ignition
SO_x	Sulfur Oxides
SSA	Specific Surface Area
SMR	Steam Methane Reformation
TDC	Top Dead Center
UHC	Unburnt Hydrocarbons
WTP	Well-To-Pump
WTW	Well-To-Wheel

transportation, researchers around the world are actively exploring strategies for reducing them. A key focus of these efforts is the adoption of renewable alternative fuels, such as biofuels [6,16–18], natural gas (NG) [19,20] and hydrogen [21]. However, the current energy landscape is still heavily dominated by exhaustible fossil fuels (NG, oil, coal), which collectively account for over 90 % of global energy demand [22–28]. NG production is generally more straightforward due to well-established extraction and processing methods. However, the environmental impact is a significant consideration.

Protecting the environment is a critical imperative, driving a wide range of efforts to reduce our reliance on fossil fuels, especially in transportation [29]. Scientists are actively exploring a variety of alternative energy sources to partially or completely replace fossil fuels. Promising alternatives include methanol [22,23,25–27], NG [30–34],

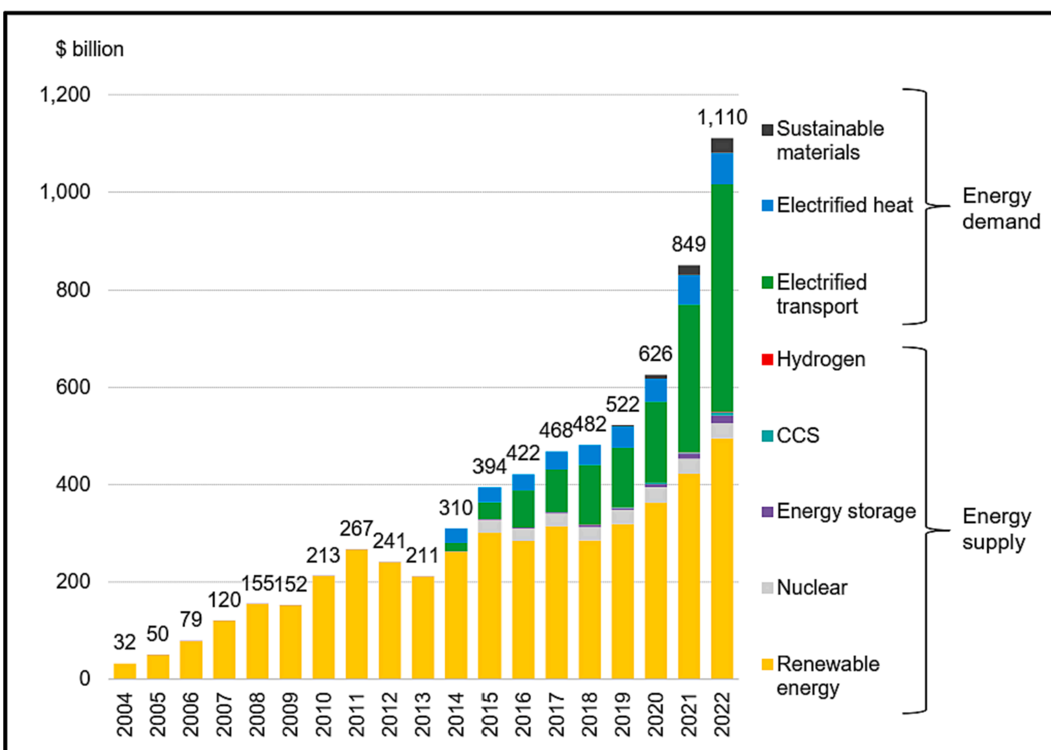


Fig. 1. Global energy transition investment by sector 2004–2022. adapted from [46]

biogas [35,36], biodiesel [37–40] and hydrogen [41–45]. These fuels are being considered as potential substitutes for diesel fuel in compression ignition (CI) engines and gasoline in spark ignition (SI) engines.

Hydrogen is the most abundant element in the universe and the most prevalent fuel. However, despite making up over 90 % of all atoms, free hydrogen is scarce on Earth. Hydrogen primarily forms compounds by binding with atoms of other elements, resulting in a diverse range of molecular configurations. Hydrogen is a versatile fuel that can be used on its own or in combination with traditional fuels such as gasoline or diesel. It is a component of hydrocarbons, including NG and of course, water (H_2O). Fig. 1 illustrates global investment trends in the energy transition sector from 2004 to 2022 [46]. In 2022, the annual global investment in energy transition technologies reached an unprecedented milestone, surpassing $1 trillion for the first time. Specifically, it achieved a remarkable record of $1.11 trillion, showcasing a notable 31 % increase compared to the previous year. This figure encompasses investments in a broad range of energy transition projects, including renewables, energy storage, charging infrastructure, hydrogen production, nuclear power, recycling, and carbon capture and storage (CCS). It also includes investments in low-carbon energy technologies for end users, such as small-scale solar installations, heat pumps, and zero-emission vehicles. Fig. 2 illustrates the projected long-term increase in demand for both NG and hydrogen.

The use of hydrogen and NG as alternative fuels has become a central focus in efforts to reduce greenhouse gas emissions and improve energy security [27,49–51]. However, it is important to note that hydrogen and NG have different properties that can affect the design, operational efficiency, and reliability of IC engines [4,52]. The global NG vehicles market is estimated to reach 42.3 million units by 2030, growing at a compound annual growth rate (CAGR) of 6.7 % from 2022 to 2030. This represents a significant increase from the estimated 25.2 million units in 2022 [53]. Fig. 3 (a) depicts historical and projected NG consumption in transport sector adapted from the US Energy Information Administration's (EIA) 2014 Energy Review [54]. It can be seen that the NG-powered medium and heavy-duty vehicles will experience significant growth in the coming decades, becoming the primary transportation user of NG. This prediction was based on the increasing availability and competitive pricing of NG compared to diesel fuel.

The global fleet of hydrogen fuel cell electric vehicles (FCEVs) increased by 40 % in 2022, reaching over 72,000 vehicles, according to the International Energy Agency's (IEA) new Global EV Outlook 2023 report [55]. Fig. 3(b) extracted from Global Hydrogen Review 2022 by IEA depicts that in 2021, hydrogen demand in the transportation sector totalled over 30 kt, a more than 60 % increase from the previous year [56]. However, hydrogen still accounts for only 0.03 % of total hydrogen demand and 0.003 % of total transportation energy. Road vehicles are the primary source of hydrogen demand in transportation, with trucks and buses consuming the majority of this hydrogen due to their high annual mileage and heavy weight relative to fuel cell electric cars. In 2021, the number of heavy-duty hydrogen trucks increased significantly (up over 60-fold from 2020), and the estimated hydrogen demand from commercial vehicles (i.e., vans and trucks) also increased.

NG is primarily composed of methane and is the cleanest-burning fossil fuel compared to oil or coal combustion [15,57]. One of the key advantages of NG is its widespread availability and existing distribution infrastructure in many regions around the world [24]. This pre-existing infrastructure facilitates the relatively seamless integration of NG into current energy systems [52]. Consequently, NG is a viable alternative fuel option that can meet the stringent engine emission regulations imposed by many countries [32,58]. NG is particularly attractive for transportation vehicles due to its abundance, relatively lower cost, reduced emissions, and compatibility with both CI and SI engines [59,60]. In a broader environmental context, NG combustion produces the least pollution among all fossil fuels, with lower emissions of particulate matter (PM) [61,62].

In the context of vehicular applications, compressed NG (CNG) and liquefied natural gas (LNG) are the two primary forms of NG [61,63–66]. CNG and LNG fuel are distinct storage formats for NG. A comparative analysis of CNG and LNG is presented in Table 1 [59,67–70]. This table provides a comprehensive overview of the key attributes of CNG and LNG fuels, highlighting the key differences between the two.

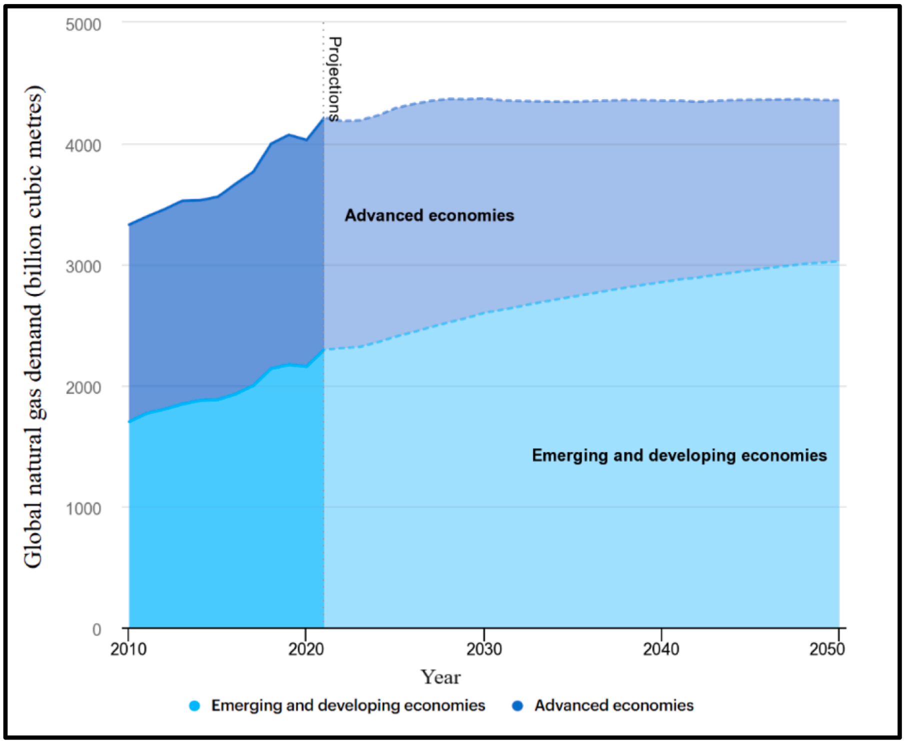
NG engines can operate efficiently under both lean burn and stoichiometric conditions [70]. The main reason why NG, which is mainly composed of methane, is such an attractive alternative fuel is its favorable chemical properties. These include a significantly high hydrogen-to-carbon (H/C) ratio and a high-octane number (approximately 130). Switching from diesel to NG results in a significant increase in the H/C ratio, from about 1.8 to a range of 3.7–4.0. Additionally, NG is distinguished by its lack of aromatic compounds such as benzene and its relatively low impurity content, characterized by fewer sulfur compounds than conventional petroleum fuels [71]. However, there are still some challenges that need to be addressed, such as reducing methane emissions, increasing engine efficiency, and extending engine life. These advances are essential for the wider adoption of NG engines in fleets as a sustainable and viable long-term technological solution, rather than relying solely on purchase incentives [32].

To improve the efficiency of NG-powered engines, various strategies have been employed [62,69]. One key approach is lean-burn combustion, which not only increases engine efficiency but also extends the vehicle's operating range. Another approach is to incorporate electronic systems, such as variable valve timing, skip-fire mechanisms, and new engine technologies, all of which improve the performance of gas engines [51]. However, it is important to note that some performance improvements may slightly reduce engine torque, making them more suitable for low-speed and low-load applications. In addition to these approaches, strategic implementation of supercharging is another effective way to improve engine dynamics [72]. Optimising fuel injection parameters, such as injection pressure, timing, and duration, is also important [60,73]. Finally, fine-tuning ignition timing, ignition energy, and valve timing is crucial for achieving higher NG engine efficiency [74]. Fig. 4 illustrates the practical embodiments of CNG and LNG engines, highlighting their diverse applications and implications [75,76].

CNG possesses a notably elevated auto-ignition temperature when compared to diesel fuel, rendering it a preferred choice for employment in SI engines [78]. However, ongoing endeavours by researchers and industries are actively exploring the adaptation of CNG as a diesel substitute within CI engines, functioning within a dual-fuel system [79,80]. This innovative approach has yielded tangible outcomes, specifically in the reduction of PM and NO_x emissions [81].

A key advantage of using CNG in CI engines is that it reduces wear and tear on moving parts compared to liquid fuels. This is because CNG generates fewer particulates, which lowers the maintenance requirements for CNG engines. However, while using CNG as a dual fuel in CI engines has potential benefits, it can also slightly increase the stress on moving parts due to the higher compression ratio (CR) and combustion temperature required [82]. Meanwhile, there is growing interest in the use of hydrogen gas in IC engines. Hydrogen is a promising fuel of the future, with no unburnt hydrocarbons, carbon oxides, or particulates [75,76,83–85].

Hydrogen is an appealing energy carrier because of its versatility and suitability for a range of applications. Its favorable physical and chemical properties make it an ideal energy carrier, and it can be produced in a variety of ways. Hydrogen supplementation in diesel engines has the potential to significantly improve performance while reducing greenhouse gas emissions and smoke. As a promising renewable alternative to conventional fuels, hydrogen offers a number of advantages, including high heating value, flame speed, diffusion rate, and rapid oxidation characteristics [84]. A study by Yilmaz et al. [86] investigated the effects of hydrogen augmentation on methane/air combustion, finding that hydrogen has a uniform impact on flame propagation characteristics and luminosity, including for methane/air mixtures, ultimately resulting in a



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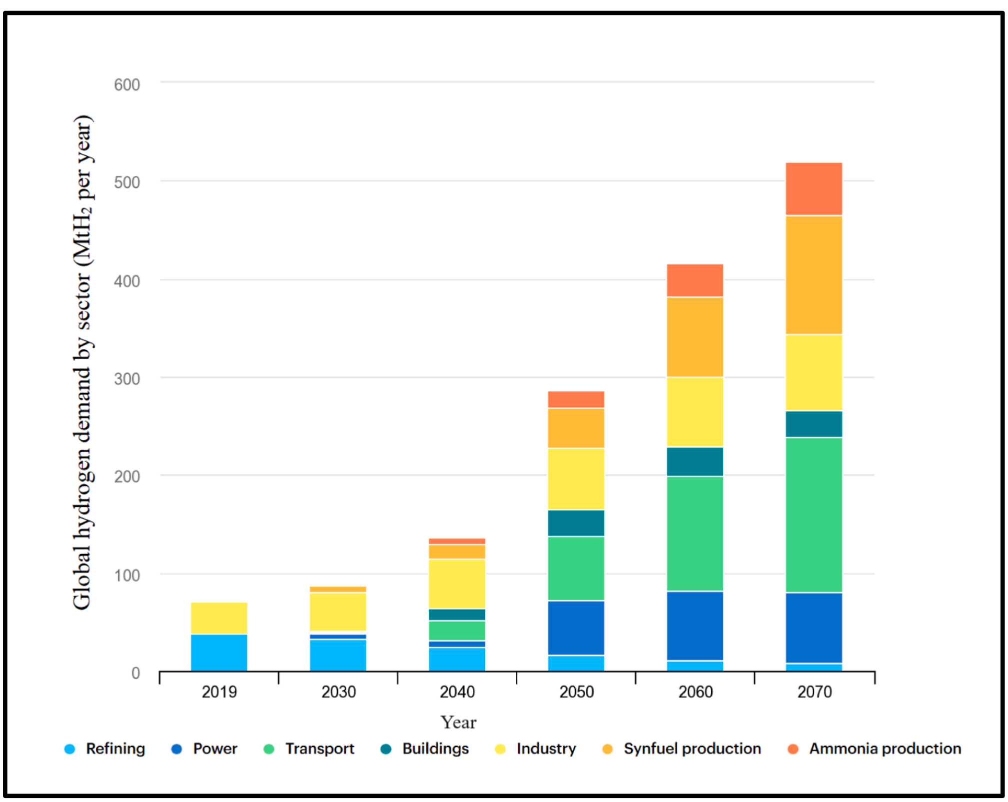

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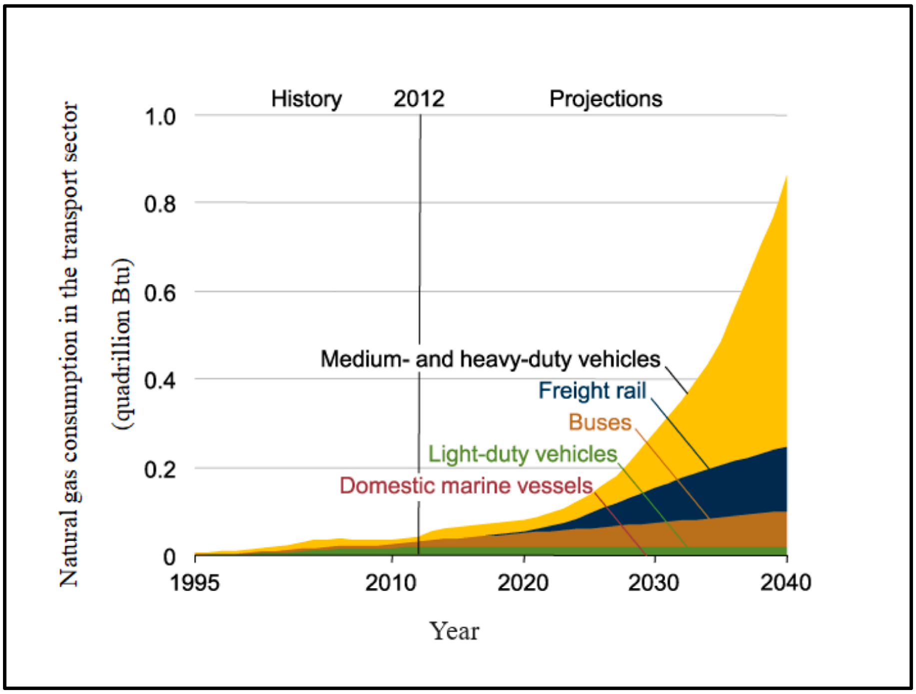
Fig. 2. (a) Global natural gas demand, 2010–2050 [47] and (b) global hydrogen demand by sector in the Sustainable Development Scenario, 2019–2070 [48].



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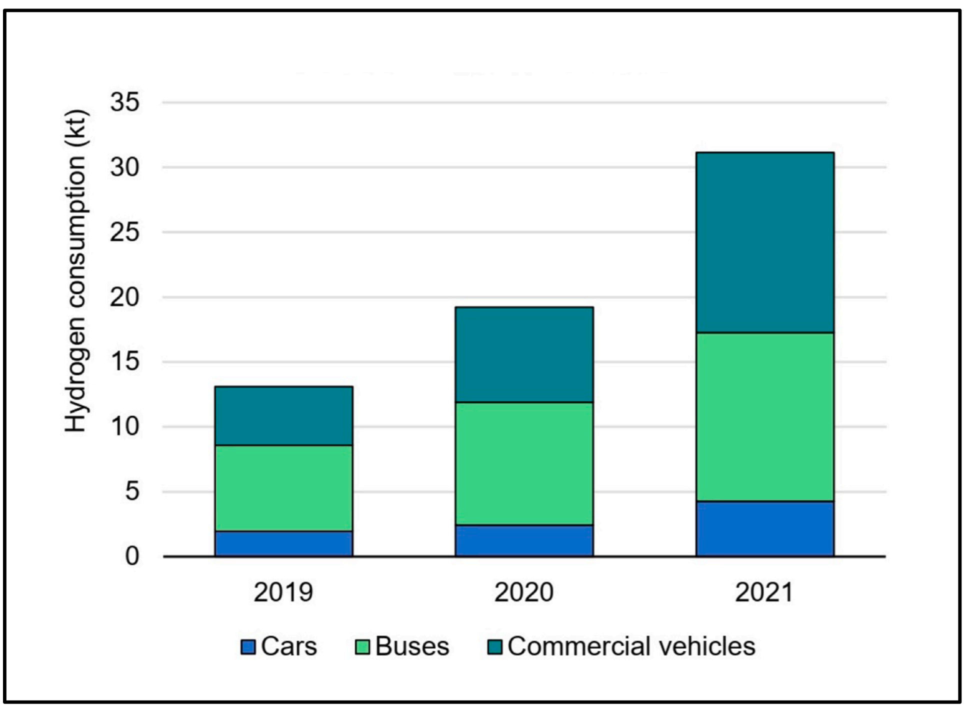

(b)

Fig. 3. (a) NG consumption [54] and (b) hydrogen consumption in the transport sector [56].

more stable combustion process. They also further explained that increasing flame speed causes the flame front to wrinkle and its surface area to increase, which improves chemical kinetics and increases the reaction rate. This leads to a higher production rate of post-combustion gases, which further propels the flame front forward.

Hydrogen has two main drawbacks that require attention. First, it tends to produce elevated levels of NO_x emissions [87]. Second, its gaseous state at room temperature and pressure makes it difficult to store and transport [85,88]. To contain significant quantities of hydrogen, high-pressure tanks or cryogenic storage systems are required. Additionally, hydrogen's buoyancy relative to air causes it to disperse rapidly in the event of a leak, making it difficult to detect and contain. This necessitates the use of specialised safety equipment and procedures to prevent leaks and mitigate the risk of fire or explosion [89].

Research on engines using alternative fuels has taken different paths, depending on the specific performance requirements and operating conditions. The increasingly stringent emissions regulations have

Table 1
Differences in properties of CNG and LNG.

Properties	LNG	CNG
Physical state	Liquid	Gas
Pressure	1 bar	100 to 250 bars
Temperature	−163 °C	30 °C to − 40 °C
Loading/Offloading	Stored as liquid	Stored as gas under pressure
Compression Ratio (CR)	~600:1	~250–350:1
Fuel tank material	Aluminum, StainlessNi Steel	Fine grain normalizedC-Mn steel,Fibre-reinforced plastic (FRP)

adapted from [59,67–70]

revived the interest in practical alternative fuel concepts. However, a key challenge is to achieve performance characteristics comparable to those of conventional diesel or gasoline engines across all operating scenarios. This challenge remains despite the evaluation of various alternative fuels for both petrol and diesel engines, with varying degrees of success. Diesel engines are well-suited for operation with several alternative fuels due to their high fuel conversion efficiencies, which are primarily attributed to their typically high compression ratios. Diesel engines that operate on alternative fuels can be classified into two distinct modes: multi-fuel and dual-fuel [90]. It is helpful to understand the difference between these two modes. A multi-fuel engine can use two different fuels to generate power, but the fuels are used separately. In contrast, a dual-fuel engine uses two fuels simultaneously.

This paper provides a comprehensive overview of the physical properties and applications of NG as a fuel in IC engines. It also meticulously summarises and categorises the challenges associated with injectors, needle valves, lubrication deficiencies, and spark plugs. Additionally, the paper reviews the production, physical characteristics, combustion attributes, and potential applications of hydrogen as an IC engine fuel. This review culminates in a concise summary of the challenges surrounding the storage, production, and safety protocols required for hydrogen utilization.

2. NG fuel

2.1. Motivation

Natural gas is a complex mixture of hydrocarbon molecules, with methane (CH_4) accounting for the majority (85–96 %) of its composition [33,91]. Other constituents include heavier hydrocarbons such as ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}), as well as inert diluents such as molecular nitrogen (N_2) and carbon dioxide (CO_2). sulfur compounds and other hydrocarbon species may also be present in natural gas. The specific composition of natural gas varies depending on the geographical source, time of year, and treatments applied during production or transportation [92].

The widespread availability and cost-effective production of NG are the main reasons for its adoption [93,94]. Compared to other fossil fuels, such as coal and oil, NG has a significantly higher reserve-to-production ratio [95,96]. Compressed natural gas (CNG) is generally used as a vehicular fuel by storing it in high-pressure tanks on board the vehicle. CNG is produced by compressing NG to high pressures, typically in the range of 200–250 bar. This compression increases the energy density of NG, making it easier to transport and store. CNG also has a cleaner combustion profile than gasoline and diesel, resulting in lower emissions of carbon monoxide, particulate matter, and nitrogen oxides (NO_x). Additionally, CNG vehicles have significantly lower operating costs than gasoline vehicles [66,97]. Moreover, CNG engines reap the benefits of diminished frictional losses, contributing to noise reduction. Additionally, the inherently lower fuel consumption of NG enhances its appeal as an economically sound fuel choice, particularly given its ready availability and cost-effectiveness. Nevertheless, the integration of NG into IC engines presents certain challenges.

Primarily, the reduced energy content of NG translates to a notable decline in maximum power, torque, and volumetric efficiency. Moreover, the prolonged combustion duration leads to a 10–20 % reduction in output power compared to conventional IC engines. The durability and aging of NG engines are subjects of concern, particularly regarding lubrication oil consumption, which could hasten the deterioration of piston seals. Such issues pose the risk of frequent downtime due to engine malfunctions, necessitating the development of seat materials and exhaust valves tailored for NG engines. Moreover, the lack of a liquid fuel spray containing detergent additives plays a role in augmenting the build-up of deposits on intake valves. The task of guaranteeing the robustness of the engine in the face of thermal stresses and the erosion of moving parts presents a significant obstacle. It is important to highlight that the longevity and trustworthiness of modern CNG engines can be enhanced by carefully choosing appropriate materials and techniques for treating the surfaces of valves, valve seats, and spark plugs.

Thorough adherence to safety protocols is imperative for CNG tankers, as the energy density of NG is 25 % less than that of gasoline. Consequently, the utilization of tanks fabricated from steel or carbon fibre is strongly advised, coupled with obligatory assessments every five years, to alleviate incidents associated with cylinders. Lastly, CNG displays an extended ignition delay period due to its diminished flame propagation velocity, thereby requiring more sophisticated spark timing strategies.

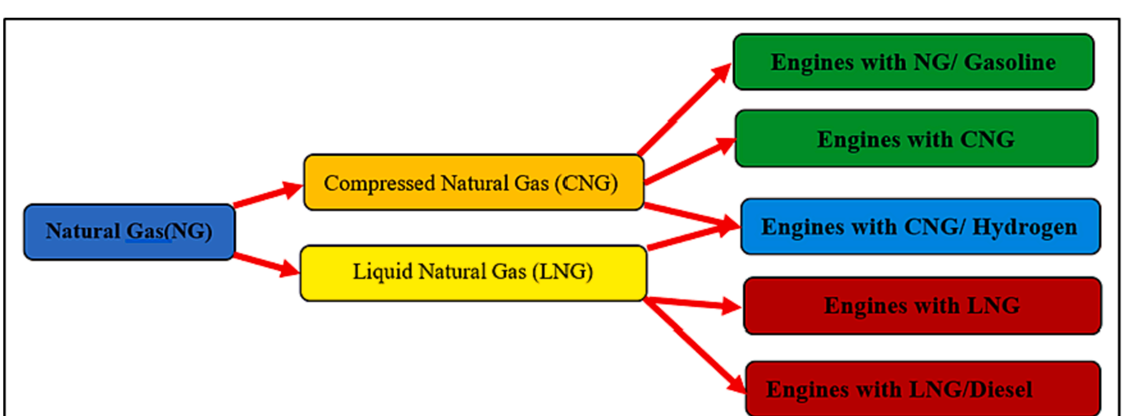

Fig. 4. Engine type and application type of CNG and LNG engines.
adapted from [77]

2.2. NG production carbon footprints

Natural gas extracted directly from wells contains various impurities, including non-methane volatile organic compounds (NMVOCs), water vapor, carbon dioxide, hydrogen sulfide, or NG liquids. Processing is required to meet purity standards for pipeline transport, referred to as "pipeline quality NG [98–100].

Emissions during the production stage arise from well-head compressors, pumps, well pad equipment, flaring systems, and compressor stations. Studies estimate that production sites and compressor stations contribute significantly to VOCs, NO_x, $PM_{2.5}$ (2.5 μm particulate matter), and SO_x emissions from NG activities [101]. Other sources of methane and NMVOC emissions include dehydrator regeneration vents, pneumatic pumps, faulty casing leaks, incomplete emissions capture, and burning in flaring systems. Some emissions are continuous or intermittent, persisting throughout a well's lifetime unless direct emissions capture and destruction or recovery measures are implemented [100].

Discrepancies in assessing the overall air quality impact of the NG production stage highlight the need for more comprehensive basin-scale studies on emissions and their effects Emissions of ozone (O_3) precursors from the NG and oil production stage have been linked to regional exceedances of ambient air quality standards, posing challenges to O_3 exposure limits [102]. High surface-level O_3 concentrations, resulting from increased NO_x and VOC abundance, can lead to respiratory problems, particularly in vulnerable populations.

There is limited information available on methane emissions from two of the three remaining stages in the NG life cycle: transmission, storage, and distribution. Due to the predominance of methane in pipeline quality NG, fewer pollutants are reported during these stages. However, the use of NG, particularly for power generation, is estimated to emit pollutants such as NO_x, SO_2, CO_2, and CH_4. Some studies attribute formaldehyde emissions and ozone concentration criteria exceedances in Texas cities to NG combustion [103].

2.3. Properties of NG fuel

NG is typically composed primarily of CH_4, which accounts for approximately 90 % of its volume. Trace amounts of ethane, propane, and carbon dioxide are also present. Ammonia is a notable contaminant in NG, and its elevated presence can increase the risk of engine corrosion. Another concern is hydrogen sulfide (H_2S), which can have detrimental effects on fuel tanks even in small quantities. This can lead to corrosion fatigue in fuel tanks, which warrants attention. In addition, NG has a significantly lower density than diesel because NG is gas and diesel is liquid [32,104 105]. As a result, LNG can store two to three times more energy in the same volume as CNG. Moreover, NG at ambient temperatures and pressures is a gas. As is typical of gases, it has a very low energy density compared to other fuels. On average, it takes 0.921 cubic meters of NG to equal the same energy content as 1 L of gasoline. This makes use of NG as a transportation fuel at ambient temperatures and pressures unfeasible[63].

However, this advantage comes at the cost of larger LNG storage tanks in the vehicle. To store LNG, a cryogenic tank operating at −165 °C is required. This allows for denser fuel storage but also reduces the available space for the vehicle's fuel tank. Compressing the gas to the required level necessitates using strong, certified tanks, typically made of materials such as steel or carbon fibre. Table 2 provides a comparison of the physicochemical characteristics of NG in contrast to those of gasoline and diesel.

Table 2
Comparison of the physiochemical properties of diesel, gasoline, NG and hydrogen fuels [63,65,68,93,106–110].

Properties	Diesel	Gasoline	NG	Hydrogen
Molar mass (kg/mol)	150–250	60–150	17.3	1
Density (kg/m^3) at 15 (°C) & 1 atm	840–880	720–780	0.72	0.085
Viscosity (mm^2/s) at 40 (°C)	1.9–4.1	0.494	–	–
Lower heating value (MJ/kg)	42.8	44	47.5–60	120
Cetane number	51	14.5–20	0	5–10
Research Octane Number (RON)	15–25	95	85–95	>130
Boiling point (°C)	180–360	38–204	−162	−252.9
Latent heat vaporisation (kJ/kg)	270	305	509–540	–
Auto-ignition temperature (°C)	180–316	258–280	595–650	585
Combustion Energy density (MJ/m^3)	36	42.7	24.6	–
Flame speed (cm/s)	2.0–8.0	37–43	20–38	185–325
Flammability limit (equivalence ratio))	0.6–2	–	–	0.1–7.1
Flammability limit (% volume in air)	0.6–7.5	–	7–21.6	4–75
Adiabatic flame temperature (°C)	2054	2150	1810	–
Stoichiometric (air–fuel ratio) mass	14.3	14.6	17.05	34.3

2.4. Spray diagnostic of NG fuel

Spray visualization and diagnostics are fundamental to the behavior of IC engines and govern the state is available for combustion. Chen et al. [111] studied the impact of different NG blending ratios on spray characteristics of under diesel rotary engine working conditions. Spray penetration was measured and analysed experimentally and numerically. The experimental results showed that the NG movement process was susceptible to the airflow motion. However, the diesel fuel distribution range was obviously enlarged under the influence of high-speed unidirectional flow. At assisted ignition timing, the stratified distributed diesel made the combustion process mainly occurred at the front and middle of the combustion chamber. Besides, the flame propagation speed was accelerated with natural gas blending ratio increasing, which effectively improved the total combustion rate. Compared to sole fuel mode, as a result of increase up to 20 % of NG blend value, the maximum combustion pressure was increased by 24.17 %. In the meantime, NO and CO_2 emissions were increased but soot and CO were clearly decreased.

Kannaiyan and Sadr [14] investigated the spray characteristics of NG fuel at high-pressure ambient conditions. The local atomization characteristics like droplet concentration, mean diameter, and droplet mean axial velocity are obtained experimentally by employing the phase Doppler anemometry technique at different conditions (ambient gas pressures of 100, 500, and 900 kPa, and ambient temperature at 400 *K*). The fuel dispersion parameters are measured at different locations far from the atomizer while maintaining the pressure differentials across the atomizer at 300 and 900 kPa. For the conditions studied, the dispersion features are greatly influenced by the ambient conditions. At higher ambient gas pressures, Gas-to-Liquid (GTL) jet fuel exhibited higher droplet concentrations, smaller droplet sizes, and smaller Sauter mean diameters than conventional fuel. These differences in droplet characteristics can have a positive impact on the energy release patterns of GTL jet fuel in a combustion environment. Pham et al. [31] studied experimentally and numerically the macroscopic of NG fuel. The macroscopic characteristics such as spray penetration, spray width, spray area and volume were measured and analysed.

2.5. Combustion properties of NG fuel

Understanding the combustion properties of both NG and CNG fuels assumes paramount significance, given their substantial impact on the performance and emissions characteristics of IC engines. Notably, the inherent low flame propagation speed intrinsic to CNG fuel contributes to an elongated ignition delay time, necessitating the application of more advanced spark timing for optimal ignition [97]. Empirical investigations have consistently highlighted the comparatively lower flame propagation speed of NG when juxtaposed with conventional fuels like gasoline and diesel [96]. To address this limitation and enhance flame speed, a viable approach involves blending CNG with fuels characterised by swifter burning rates. In this context, hydrogen emerges as a prime candidate due to its rapid flame propagation speed and notably superior lean-burn capacity, positioning it as an optimal additive for CNG. A comprehensive overview of pertinent combustion properties is furnished in Table 2, where the combustion attributes of NG, hydrogen, and diesel fuel are juxtaposed for comparison.

Gianetti et al. [112] developed and validated a CFD model of combustion model for NG engines using different piston bowls. Kim et al. [113] studied the combustion characterisation of NG in dual blend CI engines. Premixed flame regime and diffusion flame regime images were recorded. The experimental results showed that a larger NG proportion delayed flame growth for a given diesel due to the longer ignition delay. Wang et al. [114] investigated a diesel-NG dual blend combustion phase using different pilot diesel injection timings. The results showed that the injection timing has a clear impact on the process of combustion, including the combustion phases of the pilot diesel and NG consequently affecting the engine's thermal efficiency level. In addition, the chemical reaction of diesel and natural gas before combustion starts at the same time; however, the combustion duration of natural gas lags behind that of diesel. Merkel and Ciccarelli [115] investigated the ignition of methane-air with equivalence ratios of 0.25, 0.5 and 1.0. Tests were carried out at a nominal reflected pressure of 10 bar and temperatures in the range of 880–1500 K. The ignition process started with multiple flame kernels, randomly distributed throughout the mixture, which resulted in a slow rise in pressure.

2.6. Performance and emissions of NG fuel in IC engines

2.6.1. SI engines

Emissions emanating from NG engines, including UHC [50] predominantly comprise methane, a composition that can pose challenges within the context of emissions regulations. The lack of differentiation between methane and non-methane hydrocarbons within standard emissions regulations presents a notable predicament. The intrinsic difficulty in oxidising methane accentuates the issue, particularly concerning the efficacy of three-way catalysts. Mitigating HC emissions necessitates the implementation of diverse management strategies, such as optimizing mixture formation and internal flow dynamics. However, these strategies may inadvertently lead to augmented fuel consumption. Additionally, compliance with forthcoming, more stringent emissions regulations could be intricate due to the absence of catalytic control over NO_x emissions in lean conditions.

In NG engines, particularly those employing port fuel injection (PFI), there's a notable decrease in volumetric efficiency relative to sequential injection gasoline engines. This phenomenon arises from the lower latent heat of evaporation exhibited by NG. Consequently, CNG engines utilizing PFI can experience a power output loss of up to 3 %. The adoption of direct injection can enhance volumetric efficiency, thereby mitigating power output losses. Nonetheless, even with direct injection, PFI CNG engines are prone to encounter power output reductions exceeding 10 % when contrasted with equivalent gasoline engines. Consequently, optimizing, and fine-tuning engines becomes imperative to enhance the efficiency and power output of PFI CNG engines. Overcoming the challenge of maintaining power density within NG engines operating under lean conditions necessitates boosting turbocharger pressure to augment cylinder air volume. However, lean combustion under high-pressure conditions requires a substantial ignition energy input, which can impact spark plug longevity when traditional spark plug technology is employed. This reduced spark plug lifespan not only leads to heightened maintenance costs but also constrains attainable boosting pressure and lean burn limits. Addressing this challenge entails the development of robust spark plugs capable of enduring the demands of high-efficiency lean burn in NG engines. The introduction of such spark plugs not only curtails maintenance expenses but also elevates engine power output and torque, enhancing comparability with gasoline or diesel engines.

To reduce metallic nanoparticle (PN) emissions from NG engines, two primary strategies can be implemented. First, reducing the additive content of lubrication oil in these vehicles can effectively curb emissions. Second, improving in-cylinder oil seals can help to reduce PN emissions. Additionally, using exhaust particle filters is a viable method for regulating PN emissions. These strategies have the potential to significantly reduce PN emissions, leading to lower pollution levels and improved air quality. In the near future, we can expect to see a significant increase in the use of NG in automotive engines. This trend is being driven by two factors: increasingly stringent regulations on liquid-fuel-powered engines and the development of new fueling systems and combustion technologies for NG engines. As a result, automotive manufacturers and consumers are likely to become increasingly interested in NG engines, as they offer a more environmentally friendly and effective alternative to conventional liquid-fuel engines. Significant progress has been made in the development of lean-burn spark-ignited NG engine combustion systems. He et al. [116] delved into different gas injection timings (GIT), unravelling insights into the lean-burn SI NG engine's combustion system. Meanwhile, Li et al. [60] probed the optimization of combustion systems for heavy-duty NG engines, culminating in the identification of the mixed-flow intake port as an optimal performer due to enhanced in-cylinder tumble ratios and turbulent kinetic energy. Their investigation further illuminated the efficacy of an eccentric hemispherical combustion chamber (EHCC) coupled with mixed-flow intake ports for achieving superior combustion performance. However, the EHCC scheme engendered elevated NO_x emissions attributed to heightened combustion speeds and temperatures.

Pham et al. [31] conducted an experimental and numerical study of macroscopic spray characteristics. Using schlieren imaging, they investigated the effect of increased injection pressure on methane flow. They found that increasing injection pressure led to increased choking phenomena in the near-field region, but did not improve spray tip penetration.

Furthermore, Yekani et al. [51] explored the multifaceted influence of knock, performance, and economic factors within SI engines employing dual fuel of gasoline and NG. Their experimentation across four distinct gasoline-NG combinations revealed a notable correlation, with an increase in NG fraction leading to decreased standard deviation (σ) and coefficient of variation (COV) of indicated mean effective pressure (IMEP). Stettler et al. [32] conducted a comprehensive review and synthesis of emissions from LNG heavy vehicles. Their analysis found that while LNG engines have a long-term efficiency penalty of 10 %, they can reduce greenhouse gas emissions by up to 10 % compared to diesel engines. However, this reduction may not be enough to achieve net-zero emissions by 2050.

2.6.2. CI engines

Krishnan et al. [117] investigated the impact of dual blends from conventional diesel fuel and NG fuel on the performance, emissions, and heat release rate (HRR) under different operating conditions. The test results showed that there is a significant reduction in NO_x emissions under dual fuel conditions. However, unburned hydrocarbon emissions were significantly reduced because of increased NG. Moreover, the experimental results showed that at increased engine load and NG ratio, BP was decreased. However, at low loads, BP was improved.

Yang et al. [118] tested the NG and diesel fuel under co-direct injection injector strategy with a high-pressure NG DI engine. The injection pressure and ambient pressure have significant impact on gas injection duration which resulting in a significant increment in gas injection mass value.

Park et al. [24] carried out the evaluation of dual fuel of NG-diesel blend in engine work with dual blend system.

Bhowmik et al. [79] studied the performance, combustion, and emission of dual-fuel blend using several CNG strategies. They found that there is 22.57 % improvement in BTE because of using 0.02 kg/h gas flow rate and operating under 1.4 bar BMEP. Moreover, NO_x emission was reduced by 26.41 %. CO emissions were reduced by 8.17 %.

Alanen et al. [119] measured the particle emissions from a marine engine using three dual fuels. Soot mode particle emissions emitted from combustion of NG fuel was lower than soot mode particle emissions produced from the combustion of liquid fuel.

Chen et al. [120] studied a comprehensive numerical of the combustion and emission characteristics of a direct injection NG engine operating at the high load condition. The production of soot precursors reduces; thus, soot emissions reach an extremely low level. De Simio et al. [121] experimentally tested CNG dual fuel mode with external supercharging model. Soot concentration was measured. A slight increase was recorded at later start of injection. Diesel fuel soot emissions are comparable with less advanced dual fuel (NG-diesel) operating conditions. Alanen et al. [119] tested dual blend of NG and diesel with 1.4 MW marine engine with two steady state conditions under two engine loads 40 % and 85 % and kept engine speed at 750 rpm. They found that liquid fuel emitted higher soot mode particle emission higher by 4–12 times compared to that NG combustion fuel. Table 3 summarises the results of different studies fuelled with NG in gasoline or diesel engines.

From the above discussion, it can be seen that the majority of research on NG engines has focused on lean burn SI engines, which are the most common type of NG engine. In SI engines, natural gas fuel properties have a clear and direct positive effect on fuel economy and some emissions, such as CO_2 and non-methane hydrocarbons. However, the effects on other emissions, such as HC, NO_x, and CO are less clear. NG has lower NO_x emissions due to a lower adiabatic flame temperature than diesel fuel. DI NG engines also emit less PM mass than diesel engines, especially at high EGR levels. This is due to the physical and chemical differences between the two fuels. NG, which primarily comprises methane, has a lower carbon-to-hydrogen ratio (C/H) than diesel fuel. This means that when combusted, natural gas produces less CO_2 per unit of energy released than diesel fuel. A DI natural gas engine typically emits 20–25 % less CO_2 than a diesel engine [108]. However, NG combustion in an IC engine is not as complete as diesel fuel combustion, due to its slower burning rate. This results in higher unburnt HC emissions from a DI NG engine than from a diesel engine, but lower than from a premixed NG engine. Furthermore, it was indicated that adding ethane, propane, hydrogen, and nitrogen to the fuel had no significant effect on the engine's power or fuel consumption. Emissions of unburned fuel were reduced for all additives and PM emissions were increased by ethane and propane but are virtually eliminated by including nitrogen or hydrogen in the fuel.

CNG DI combustion achieves shorter combustion duration and comparable combustion efficiency to homogeneous mixture combustion. However, NO_x emissions are high, while CO emissions remain low. In dual fuel (DF) engines, the in-cylinder pressure during compression and the initial stages of combustion is slightly lower than in diesel engines, and the ignition delay is longer [129]. The peak in-cylinder pressure, pressure rise rate, and heat release rate under DF mode are all strongly correlated with the pilot diesel injection parameters. Increasing the pilot diesel injection can extend the lean burn limit and reduce HC and CO emissions, but it has the opposite effect on NOx emissions [130]. At low loads, DF engines always produce smokeless exhaust, and even at full loads, smoke emissions are still lower than those from diesel engines.

2.7. Challenges of NG as a fuel

2.7.1. Injectors and needle valve problems

NG blends led to several issues in injection system especially in the injectors and the needle valves [131]. One issue of CNG fuel is had lower fuel density as well as a lower volumetric energy density compared to diesel or gasoline, whether stored either as gas in CNG tanks or as liquid in LNG tanks [108,132]. Therefore, the injectors and the needle valves used for CNG must be designed to handle the higher flow rates and lower densities of the gas. Injectors can become clogged or malfunction if the wrong injectors are used or if they are not properly maintained [133,134].

Another issue is that CNG is stored at high pressures, typically around 200–250 bar. Therefore, the injectors and the needle valves must be able to withstand these high pressures and prevent leaks or other failures. If the injectors and the needle valves are not designed to handle these high pressures, they can become damaged or fail, leading to poor engine performance or even engine damage [66,74].

Another challenge with CNG is that it is highly reactive and can corrode certain materials, especially those containing copper or other metals that are prone to corrosion. This can reduce engine performance and increase maintenance costs. To mitigate this, corrosion-resistant materials such as stainless steel and aluminum are used for injectors and the needle valves that are exposed to CNG [82].

A CNG vehicle travels about 38 % of the distance of an LNG vehicle, 25 % of the distance of a gasoline vehicle, and 23 % of the distance of a diesel vehicle, given the same fuel tank size and fuel consumption rate. In other words, a CNG tank would need to be about four times larger than a diesel tank to travel the same distance, and a LNG tank would need to be about 70 % larger than a diesel tank [108].

Lastly, CNG injectors require more precise metering than traditional liquid fuel injectors so needle valves need to be used to control the fuel flow into the engine. In CNG engines, needle valves are typically used in conjunction with injectors to meter the precise amount of fuel needed for combustion. If the needle valves are not functioning properly, this can lead to a lean fuel mixture and engine misfiring, which can cause poor engine performance and increased emissions [118].

2.7.2. Lack of lubrication problems

When using CNG blend in IC engines, another main problem that can arise is a lack of lubrication compared to diesel or gasoline blends: CNG is a gaseous fuel, and it does not contain the lubricating properties that are present in liquid fuels [63].

This lack of lubrication can cause wear and tear on engine components, particularly on the cylinder walls, piston rings, and valve train. Consequently, it can lead to increased maintenance costs and reduced engine lifespan. To mitigate this issue, CNG engines typically use a lubrication system that is separate from the fuel system. This system uses oil to lubricate the engine components and prevent wear and tear. This can include the use of an oil pump, oil filter, and oil cooler to ensure proper lubrication and temperature control [119].

Another solution is to use special lubricants that can withstand the high temperatures and pressures of CNG combustion. These lubricants are specially formulated to provide the necessary lubrication for CNG engines, even in the absence of the lubricating properties of liquid fuels. Additionally, CNG engines require a higher compression ratio than gasoline engines. Therefore, compression ratio has be to maintain to prevent wear and tear on engine components.

Overall, the lack of lubrication can be a major problem when using CNG as a fuel in engines. To prevent premature engine failure and maximize engine life, it is important to use the correct lubricants and oil-injection systems when operating CNG engines.

2.7.3. Spark plugs problems

When CNG blend is used as a fuel in engines, spark plug fouling can be a common issue. This is because CNG is a relatively clean-burning fuel that does not supply as much heat as other fuels, resulting in inefficient combustion. This can lead to a build-up of carbon deposits on the spark plug, which can prevent it from firing properly. The best way to prevent spark plug fouling is to ensure that the engine is properly tuned and that the spark plugs are replaced regularly. If spark plug fouling does occur, it can be cleared out by cleaning the spark plug with a wire brush or by using a spark plug cleaner. If the fouling is severe, it may be

Table 3
Results of engines fuelled with NG in SI and CI engines.

Author	Fuel %	Operating Conditions	Engine type	Finding
Yekani et al. [51]	Dual fuel: NG & gasoline.	• G100, G87.5, G75, G62.5 62.5 % using stoichiometric conditions. • 1800 rpm engine speed was used in the test. • CR 10 was used in the test.	• Motor vehicles SI engine	• The high NG ratio in the dual blend resulted in increasing the standard deviation. However, coefficient of variation of IMEP was decreased. • The high NG ratio in the dual blend resulted in increasing the unit price per work induced.
Divekar et al. [78]	Dual fuel: NG & gasoline.	• Engine speeds: 600,1500,2000, 3500 & 4000 rpm. • 5 Engine load: 0 %, 25 %, 50 %, 75 %, 90 % and 100 %.	• 8-cylinder, SI engine with PFI system. • Two sparks plug ignition system were used in the engine test.	• NG fuel resulted in pumping loss reduction which led to reduce fuel consumption. • Stable combustion occurred with increased load operation of NG fuel resulted in increased knock resistance. • The experimental results showed that peak power performance increased by 4 % & CO_2 emissions reduced by 22.5 % at peak power operation.
Nikbnam et al. [80]	Dual fuel: NG & gasoline.	• 5 Engine speeds: 1200, 1400, 1600, 1800 & 2000 rpm	• 4-cylinder CI engine	• The maximum torque of the engine carried out by dual fuel NG& diesel was lower by 7.2 % compared to the test run by diesel fuel. • Dual fuel NG & diesel blends test emitted high NO*x*, HC, CO_2 & CO emissions by 20, 53, 16 and 86 %, respectively compared to diesel fuel test at engine speed 2000 rpm. • Conversely, O_2 and soot emissions were significantly reduced using dual fuel NG & diesel blends by 51 % and 69 % respectively compared to diesel blend test at engine speed 2000 rpm.
Shuai Feng et al.[116]	Different NG compositions fuel.	• Injection timings (GIT) were variable. • CR 16.5 & 11 were used in engine test using low load conditions.	• 2135G −2- cylinder SI -NG engine.	• The combustion status between the 2–8 engine cycles have a certain degree of correlation, while the correlation becomes extremely weak after more than 8 engine cycles. • The correlation between engine cycles only exists between 2 and 4 engine cycles when the combustion is the extremely unstable (GIT = 60∘CA ATDC).
Alanen et al. [119]	Dual fuel: NG & MGO & MDO	• Two steady state conditions with 40 % & 85 % load. • Engine speed kept at 750 rpm.	• 1.4 MW marine engine	• Liquid fuel combustion of liquid fuel emitted higher soot mode particle emissions higher by 4——12 times compared to the combustion of NG fuel.
Behrad et al. [122]	Dual fuel: NG & gasoline.	• Four ratio of ng fuel with gasoline: GA100, GA90, GA80 & GA70. • Equivalence ratio was used: 1.0 with CR was: 11. • 3 Engine speeds: 1500, 1800, & 2100 rpm.	• A single cylinder SI engine with adjustable speed.	• Increasing NG ratio in the blend led to increased $\Delta\theta$ (the distance between optimum spark advances and the impending knock limit advance.
Krishnan et al. [123]	Dual fuel: NG & diesel.	• Small diesel engine single cylinder	• Using a pilot ignition strategy	• NO*x* emissions were reduced between 0.07 and 0.10 g/kWh compared to diesel blend test. • NG fuel test emitted higher HC & CO emissions compared to diesel blend test.
Mbarawa [124]	Dual fuel: NG & diesel.	• Under constant-volume conditions. Three-dimensional (3D) model • Four different NG (NG 1, NG 2, NG 3, and NG 4) compositions with air ignited by the pilot diesel spray injected at the different injection pressure (20, 30, 60, 90 and 120 MPa).	• Using numerical model	• ↑ NG mixture leads to ↑ in the NG burning. • Higher injection pressure improves the DF combustion processes.
Karavalakis et al.[125]	Different NG compositions fuel.	• Operated over different driving cycles. • Each vehicle was tested on each fuel over three Federal Test Procedure (FTP) and three Unified Cycle (UC) tests.	• Two light-duty vehicles (a 2002 Ford Crown Victoria and a 2006 Honda Civic GX)	• Modern light-duty NGVs, fuel properties have a clear and direct impact on fuel economy and some emissions compo-nents, such as CO2 and NMHC, but not for other emission components, such as THC, NO_x, and CO. • Changing fuel composition impacted NO_x emissions showed only limited fuel effects for the two vehicles.
Vavra et al. [126]	Different NG compositions fuel.	• Full load and various engine speeds.	• A light duty turbocharged stoichiometric SI truck engine with a	• The addition of gaseous higher hydrocarbons worsens the knock

(*continued on next page*)

Table 3 (*continued*)

Author	Fuel %	Operating Conditions	Engine type	Finding
			wastegate turbocharger & cooled EGR	resistance of the fuel and necessitates a retarding of the spark timing. • The addition of gaseous higher hydrocarbons slightly worsens the emissions of CO_2. • Engine power and efficiency are improved by an increased mixture volumetric CV, higher burning velocity and higher boost pressure (at low engine speed.
Hajbabaei et al. [127]	Different CNG compositions of fuel.	• Six tests were run on each vehicle/fuel combination for all vehicles.	• Three buses were used. equipped with a 2009 stoichiometric SI Cummins Westport ISL G8.9 L engine with a TWC and a cooled EGR system, • A bus equipped with a 2004 John Deere 8.1L 6081H lean burn engine & a bus equipped with a 2003 8.3L Cummins Westport C-Gas Plus lean burn engine.	• For the lean burn buses, gases with low methane contents exhibited higher NOx (nitrogen oxides) (19 %e53%) and NMHC (non-methane hydrocarbon) (39 %e102%) emissions. • Lower emissions of THC (total hydrocarbon) (9 %e24%), CH4 (methane) (23 %e33%), and formaldehyde emissions (14 %e45%). • The stoichiometric engine bus with a TWC showed significantly reduced NOx and THC emissions compared to the lean burn buses but did show higher levels of CO & NH3. • PM did not show any fuel effects, while PN exhibited some reductions for the higher WN gases
McTaggart-Cowan et al. [128]	NG fuel with the effects of adding ethane, propane, hydrogen, and nitrogen.	• The additives to NG gas were propane, ethane, hydrogen and nitrogen; pure methane was also used as a comparison to the NG. • Engine speed 1200 RPM.	• A single-cylinder research engine equipped with a prototype fuelling system. Direct injection; diesel pilot, gaseous main fuel. • A Cummins ISX series modified.	• These additives had no significant effect on the engine's power or fuel consumption. • Emissions of unburned fuel are reduced for all additives through either enhanced ignition or combustion processes. • Black carbon particulate matter emissions are ↑ by ethane and propane but are virtually eliminated by including nitrogen or hydrogen in the fuel.

necessary to replace the spark plug. Finally, it is important to use the correct spark plug for the type of fuel being used. For example, spark plugs designed for use with gasoline may not be suitable for use with CNG. Using the wrong type of spark plug can lead to increased fouling and poor performance [64].

2.7.4. Challenge of NG storage requirement

Storing NG is more challenging than storing liquid fuels such as diesel or gasoline. NG has a lower energy density per unit volume than liquid fuels. NG can be stored and used in two forms: CNG and LNG. CNG is more widely used in vehicles than LNG, primarily because it is less expensive and easier to store and handle.

However, liquefying NG can improve its performance as a fuel. Pospíšil et al. [135]discussed the potential benefits of LNG, including its higher energy density and easier transportation due to its liquid form. However, liquefaction requires significant energy input, which can offset some of the benefits. Therefore, the choice between CNG and LNG for vehicle fueling depends on a variety of factors, such as cost, availability, and infrastructure requirements.

3. Hydrogen fuel

3.1. Motivation

Hydrogen is gaining significant momentum as a viable alternative to fossil fuels, which pose a number of challenges, including global warming, fluctuating prices, and supply concerns [136]. The advent of the automobile led to a rapid increase in fossil fuel production and combustion, revolutionizing transportation, and trade. However, this has also caused significant environmental damage. To meet the energy demands of a growing global population while reducing emissions, there is a pressing need for long-term solutions. While clean energy sources such as wind and solar power are promising, they require storage and transportation carriers. Hydrogen has lower environmental impacts, and it can serve as a carrier for these sustainable energy sources. Therefore, hydrogen energy offers a promising solution to the challenges posed by fossil fuel dependency. It can provide a clean and sustainable source of energy to meet the needs of the growing world population while minimizing the adverse environmental impacts caused by fossil fuels. Additionally, the use of hydrogen as a carrier for renewable energy sources enhances the adaptability and reliability of these resources, making them more feasible for widespread use. In conclusion, hydrogen energy has the potential to play a critical role in the transition towards a lower-impact future [83,137,138].

3.2. Hydrogen production

Hydrogen is currently primarily produced from fossil fuels, but it has the potential to be a commercially mature, cost-effective, and highly-efficient technology [139]. Hydrogen production from fossil fuels can be achieved through two methods: hydrocarbon reforming and pyrolysis [140]. Reforming technology is a widely used method for producing hydrogen from hydrocarbon fuels. The most common method is steam methane reforming (SMR), which is used extensively in refineries. Other methods include partial oxidation (POX), autothermal reforming (ATR), and dry reforming (DR).

- Steam Methane Reforming (SR): Steam methane reforming (SMR) is a mature technology for producing hydrogen from NG [141]. It is the most common method for producing hydrogen today, and it is used in a variety of applications, including refineries, fertilizer production, and hydrogen fuel cells. SMR is a two-step process. In the first step, natural gas is reacted with steam at high temperatures over a catalyst to produce hydrogen and carbon monoxide. The reaction is endothermic, meaning that it requires heat to proceed. The heat is typically supplied by burning a portion of the natural gas. In the second step, the carbon monoxide is reacted with steam to produce additional hydrogen and carbon dioxide. The reaction is exothermic. The heat from this reaction can be used to preheat the feedstock and reaction mixture, which helps to improve the overall efficiency of the process.

- Partial Oxidation (POX): POX is a less common method for hydrogen production than SMR [142]. It involves reacting hydrocarbons with air or oxygen at high temperatures to produce hydrogen and carbon monoxide. POX can be more efficient than SR, but it also produces more nitrogen oxides, which are pollutants. Besides, the hydrogen generation efficiency for SMR ranges from 65 % to 75 %, while POX process efficiency for methane is estimated to be around 50 % [143].
- Autothermal Reforming (ATR): ATR is a newer method for hydrogen production that is still in development [144]. It combines the features of SR and POX to produce hydrogen more efficiently. ATR involves reacting hydrocarbons with a mixture of steam and air or oxygen at high temperatures.
- Dry Reforming (DR): DR is a less common method for hydrogen production than SMR, POX, or ATR. It involves reacting hydrocarbons with carbon dioxide at high temperatures over a catalyst to produce hydrogen and carbon monoxide [145]. DR is a more energy-efficient method for hydrogen production than the other methods, but it also produces more greenhouse gases.

Hydrogen produced from sustainable sources is known as “green” hydrogen. Green hydrogen can be produced through biomass, derived from plant and animal-based materials, is a renewable energy source gaining popularity due to its sustainability and low environmental impact [38]. Biomass conversion technologies are categorized into thermochemical and biological pathways. Thermochemical pathways, including pyrolysis, gasification, combustion, and liquefaction, transform biomass into hydrogen and hydrogen-rich gases [146]. Biological pathways, encompassing biophotolysis, photofermentation, dark fermentation, and biological shift reactions, enable hydrogen synthesis from biological sources [147]. Green hydrogen can also be produced through biological pathway using biomass which includes bio-photolysis, dark fermentation, and photo fermentation [148]. In contrast, the thermochemical route consists of processes such as pyrolysis, gasification, combustion, and liquefaction [149].

Green hydrogen can also be produced using renewable energy sources like solar and wind power to electrolyze water into hydrogen and oxygen. Water electrolysis is a zero-emission technology that splits water molecules into hydrogen and oxygen using electricity. Electrolyser cells can be powered by renewable energy sources, like solar and wind power, or waste heat from industrial processes. There are four main types of water electrolysis technologies: alkaline, anion exchange membrane (AEM), proton exchange membrane (PEM), and solid oxide electrolyzers (SOEC) [150]. All four technologies work on the same principle using electricity to split water molecules into hydrogen and oxygen. Fig. 5 illustrates the hydrogen production pathways from fossil fuels and renewable sources.

The future of hydrogen production is likely to be a mix of different technologies. SMR will likely continue to be used for large-scale hydrogen production, but renewable sources are expected to play an increasingly important role. Electrolysis is expected to be the most common method of producing hydrogen from renewable sources, but thermochemical cycles and biological processes may also play a role.

3.3. Properties of hydrogen fuel

Hydrogen is an odorless, colourless, and tasteless gas that is non-toxic, has low density, and is highly flammable even at low temperatures. It is the lightest and most abundant element in the universe, comprising around 75 % of its elemental mass. Hydrogen exists in various forms, including diatomic molecule (H_2), atomic hydrogen, and hydrides [152].

One of the most significant characteristics of hydrogen is its high reactivity, which enables it to easily form chemical compounds with many other elements. This property makes it a versatile element suitable for various applications, such as fuel cells, rocket propulsion, and industrial processes.

Another crucial feature of hydrogen is that it is a clean-burning fuel, producing only water vapor when burned with oxygen. This quality changes hydrogen into a renewable alternative source to conventional fuels that emit carbon dioxide and other hazardous pollutants and, therefore, mitigation the impact of climate change can be achieved by using renewable source fuel that emitted low greenhouse gas emissions.

However, in gaseous state hydrogen has a very low density, which is

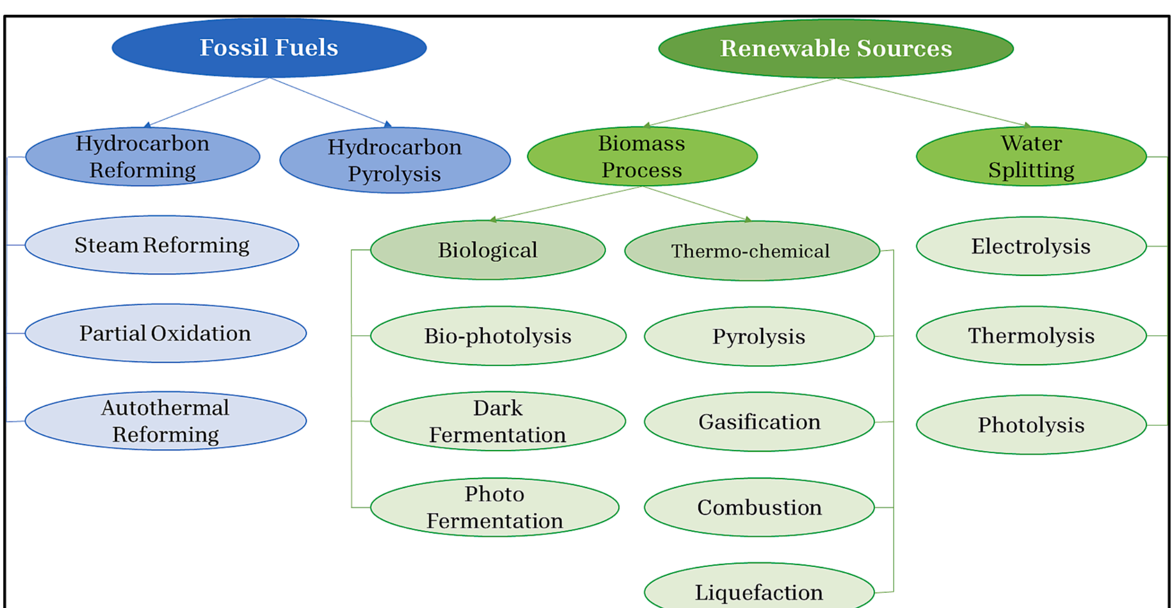

Fig. 5. Hydrogen production methods [151].

one-fourteenth that of air, making it much lighter than other gases. Therefore, hydrogen requires high pressure or cryogenic temperature for storage in reasonable quantities.

In summary, hydrogen possesses several properties that make it an alternative energy source for a sustainable future. Its high reactivity, versatility, clean-burning nature, and low density make it an ideal choice for various applications, including fuel cells, rocket propulsion, and industrial processes.

3.4. Injection diagnostic of hydrogen fuel

Injection visualization is an important section before understanding combustion of hydrogen fuel in IC engines as sole fuel or dual blend. Combustion characteristics are significantly affected by injection process. Babayev et al. [153] studied the computational characterization of hydrogen direct injection and nonpremixed combustion in a CI engine. They measured jet tip penetration at three pressure ratios as a function of time. In addition, simulation results were compared to experimental. Wang et al. [154] studied the hydrogen jet characterises of an outward-opening injector using high speed schlieren in a constant volume chamber at different injection and ambient pressure ratios (PR). The experimental results showed that the hydrogen jet in the near-field is a conical structure, while the jet structure develops into a spherical vortex in the far-field. The jet axial penetration, radial penetration, and volume increase with the increasing of the PR. The normalization analysis of jet penetration shows that the hydrogen jets have a good self-similarity under all PRs. A non-dimensional scaling correlation of axial penetration is proposed for this kind of hydrogen jets. In the scaling correlation, the exponents of the non-dimensional penetration and time term are 0.18 and 0.83, while the penetration constant is 13.18. The discovery of the above jet characteristics can predict the free jet shape under any PR in the range of 10 to140. These results can also promote the application of DI hydrogen engines.

3.5. Combustion properties of hydrogen fuel

Hydrogen displays a variety of properties that enhance its suitability as a combustible fuel. Firstly, it possesses a broad flammability range, allowing for efficient combustion across a range of hydrogen concentrations in air or other oxidizing agents. Consequently, combustion of hydrogen in IC engine can be used under different fuel–air ratios. One notable benefit is that hydrogen can operate using fuel amount with less than the stoichiometric amount required for combustion with a given air quantity called lean mixture. Therefore, it is relatively effortless to initiate an engine using hydrogen. Typically, when a vehicle runs on a lean mixture, it achieves lower fuel consumption and efficient reaction during the combustion. Moreover, the internal temperature of the combustion is generally lower, which decreases exhaust emissions, such as NO_x. However, there is a limit to the extent to which the engine can be operated using a lean mixture, consequently, the BP could be reduced because the volumetric heating rate of the air -fuel ratio was reduced.

Secondly, hydrogen exhibits a notably low ignition energy, implying that a mere fraction of energy input is necessary to commence the combustion process. The energy imperative for instigating hydrogen combustion is roughly one order of magnitude less than the demand for gasoline ignition. This particular attribute empowers hydrogen-fueled engines to effectively initiate combustion in lean mixtures and guarantees a rapid and punctual ignition sequence.

However, the trade-off associated with this reduced ignition energy is the potential emergence of issues such as early ignition and flashback [155]. Flashback is the occurrence of the flame propagating back upstream from the combustion chamber towards the fuel source. This phenomenon can result in various issues, including damage to the engine components such as the intake manifold, valves, and turbocharger due to a sudden increase in pressure. It also leads to reduced engine efficiency by disrupting the normal combustion process. Additionally, flashback contributes to increased emissions, particularly NO_x, from the engine. This risk arises due to the possibility of hot gases and heated spots within the cylinder serving as plausible sources of ignition. Various strategies can be employed to mitigate flashback in hydrogen engines [156]. One effective method involves the use of flame arresters, devices installed in the fuel line to prevent the flame from propagating upstream by quenching it. Another approach is the utilization of mixers, devices that blend hydrogen fuel with air before entering the combustion chamber. Maintaining a continuous pilot flame in the combustion chamber is another preventive measure, ensuring more even ignition of the hydrogen-air mixture and reducing the likelihood of flashback. Additionally, implementing a stratified charge combustion system [157], where fuel and air are intentionally not mixed evenly in the combustion chamber, helps control the combustion process and lowers the risk of flashback. Lastly, blending hydrogen with other fuels, like natural gas or methane, can decrease the overall reactivity of the fuel mixture [158], although this may impact the energy density and efficiency of the fuel.

Thirdly, hydrogen exhibits a reduced quenching distance, which is smaller compared to gasoline. As a result, hydrogen will only be extinguished in closer proximity to the cylinder wall compared to flames of other fuels. This attribute renders the suppression of a hydrogen flame more intricate compared to managing a gasoline flame because more of the flame can be outside the quenching distance, thereby having sufficient energy to reignite any portion of the flame that experiences quenching. Furthermore, the reduced quenching distance may elevate the potential for backfiring occurrences, as a hydrogen-air flame is more prone to pass through an almost closed intake valve when contrasted with a hydrocarbon-air flame.

Additionally, hydrogen demonstrates a high autoignition temperature (858 K), which enables the utilization of larger CRs in hydrogen engines compared to gasoline engines [159]. In contrast, endeavours to initiate ignition in a CI or diesel setup with hydrogen are confronted with difficulties stemming from the relatively elevated temperatures imperative for such ignition modes.

Furthermore, hydrogen exhibits a high laminar flame speed at stoichiometric ratios compared to diesel and gasoline [160]. In addition, the laminar flame speed of hydrogen is nearly ten times higher than that of methane [161]. This characteristic allows hydrogen engines to approach the thermodynamically ideal engine cycle more closely. However, as the mixture becomes leaner, the flame speed of every fuel decreases significantly, but because of the wide flammability of hydrogen it is possible to operate at conditions where the flame speed is close to those of near-stoichiometric hydrocarbons.

Finally, hydrogen possesses high diffusivity, enabling it to rapidly mix and disperse in gaseous environments. This property is advantageous for achieving uniform fuel–air mixtures, promoting efficient combustion. Last, hydrogen has an exceptionally low density, which gives rise to two challenges when employed in an IC engine. First, a substantial volume is required to store a sufficient amount of hydrogen to provide a vehicle with an acceptable driving range. The energy density of a hydrogen-air mixture, and consequently the power output, is diminished. In conclusion, these properties collectively enhance the suitability of hydrogen as a combustible fuel, making it an attractive option for numerous energy-related endeavours.

3.6. Performance and emissions of hydrogen in IC engines

The use of hydrogen as a viable fuel source for SI engines to achieve superior performance has gained significant attention. Hydrogen exhibits favorable properties such as rapid flame propagation, low ignition energy, and a wide operating range. These qualities facilitate the optimization and enhancement of the combustion process, which can help to effectively reduce the emission of harmful constituents, particularly NO_x emissions, among other associated benefits [162–166]. There are three primary methods for incorporating hydrogen into SI engines: manifold induction, direct injection, and hydrogen addition to gasoline, each with its own specific procedures and advantages. In the manifold induction method, hydrogen at lower temperatures is introduced into the manifold using a duct regulated by a valve [167]. The direct introduction method, on the other hand, entails the circulation of liquid hydrogen from a cryogenic cylinder to a heat exchanger via a pump, resulting in vaporisation. Subsequently, cold hydrogen is injected into the engine [168] This particular technique effectively mitigates pre-ignition and contributes to a notable reduction in NO_x emissions throughout the combustion process. Finally, the strategy involving the addition of hydrogen to gasoline encompasses the introduction of a blend of hydrogen and gasoline into the engine's combustion chamber. The ignition of the compressed mixture is achieved through a spark [169].

On the other hand, in CI engines, the principal fuel is diesel, and combustion is regulated by introducing hydrogen as an additive to modulate combustion phasing [170]. There are two methods for adding hydrogen: 1. Direct injection of varied amounts into the combustion chamber (non-homogeneous mixture production) and 2. Through the input manifold (homogeneous mixture creation), while the diesel is fed into the combustion chamber as normal. The use of hydrogen as a fuel for diesel engines poses significant challenges due to its unique properties, including a wide flammability range, high flame speed, low ignition energy, low energy density, and high diffusivity compared to diesel fuel. These properties add complexity to the use of hydrogen in diesel engines, as evidenced by specific issues related to its application [171,172]. These issues encompass the propensity for uncontrolled ignition resulting in inlet backfiring, in-cylinder combustion with increased heat release rates and potential knocking (indicated by higher maximum pressure rise rates and abrupt engine operation), as well as elevated levels of NO_x and challenges pertaining to hydrogen storage. As a result of these challenges, using hydrogen as a supplementary fuel in diesel engines is a more attractive option than using it as the sole fuel [173,174].

3.6.1. SI engines

When hydrogen is employed either as an added fuel or as the primary fuel in SI engines, it permits operation using a leaner mixture than conventional conditions. Analysis of various research studies suggests that engines operated with hydrogen as an added fuel alongside a lean mixture exhibit a decrease in emissions of NO_x [175,176]. When hydrogen is burned in internal combustion engines, a small amount of HC, CO, and CO_2 emissions are produced due to the combustion of lubricating oil on the surfaces of the engine cylinders [177].Moreover, SI engines that use hydrogen as fuel exhibit reduced heat transfer from the cylinder to the cooling water when compared to engines fuelled by diesel and gasoline, resulting in higher thermal efficiency [178]. In general, the power reduction caused by the throttle in SI engines can be circumvented by directly injecting fuel into the cylinder, replacing the hydrogen intake line[166]. Similarly, several investigations have examined the integration of hydrogen into SI engines and have indicated that it enhances performance by increasing flame velocity [179,180]. By delivering the mixture to the cylinder without the requirement for a throttle, the wide ignition range of hydrogen can contribute to a reduction in pumping losses [181].

Al-Baghdadi [182] conducted an experimental investigation to evaluate the operational characteristics and emission levels of a four-stroke SI engine when fuelled with various blends of hydrogen and ethanol. The tests were conducted using hydrogen-ethanol blends containing 2 %–12 % by mass. Gasoline fuel was utilised as a reference for comparative purposes. According to his findings, the utilization of ethanol fuel at a CR of 12, along with the addition of hydrogen (0–3.5 % by mass), resulted in lower emissions compared to gasoline fuel at a CR of 7. Moreover, the engine exhibited a higher power output across all hydrogen percentages in ethanol compared to pure gasoline fuel. Heffel [183] conducted experiments on a 2L, 4-cyl. Ford ZETEC gasoline engine that was modified to run on hydrogen fuel. The purpose was to investigate the impact of exhaust gas recirculation (EGR) on combustion behaviour and the emissions of NO_x. His results indicated that adopting this method was an effective way to decrease NO_x emissions in a hydrogen-fuelled engine, achieving levels below 1 ppm.

In their research, Subramanian et al. [184] carried out investigations using a hydrogen-fueled SI engine with a singular cylinder configuration. This experimental setup involved the utilisation of electronically regulated timed manifold injection for fuel delivery. The main objective of their work was to investigate the effectiveness of NO emission control techniques, specifically water injection into the intake manifold and spark timing retardation. The hydrogen-fuelled engine exhibited a maximum power output equivalent to approximately 78 % of the rated power achieved with gasoline. In addition, despite operating with lean mixtures, the hydrogen-fuelled engine exhibited significantly low cycle-by-cycle variations in combustion rates, owing to high combustion rates. However, this led to elevated temperatures and subsequent NO emissions, with the peak HRR being nearly double that of gasoline operation.

Ji and Wang [169,185]conducted experiments using a modified four-cylinder hybrid hydrogen-gasoline engine. This engine was equipped with an electronically regulated hydrogen port injection system and a hybrid electronic control unit. The results from these experimental endeavours unveiled that the BMEP of the engine encountered augmentation solely during conditions of diminished load subsequent to the introduction of hydrogen. Furthermore, the BTE of the engine displayed enhancement with the incorporation of hydrogen. Noteworthy observations encompassed an elevation in cylinder temperature and peak cylinder pressure, alongside reductions in the durations pertaining to the ignition flame's development and propagation, correlated with escalating levels of hydrogen augmentation. Moreover, emissions of HC and CO exhibited a decrease, while NO_x emissions displayed an increase in consonance with higher engine loads and increased levels of hydrogen in blends.

Jingding et al. [186] observed that the hydrogen-enriched gasoline engine exhibited lower HC and CO emissions compared to the original gasoline engine. They reported that when hydrogen is introduced into a gasoline-air mixture, it primarily engages in oxidation reactions with oxygen. As a result, the concentration of NO produced by the oxidation reactions of nitrogen is approximately reduced by a factor of one compared to when hydrogen supplementation is not present. They also reported that, the addition of hydrogen significantly enhances the concentration of hydroxyl radicals (OH), thereby accelerating the oxidation reaction of CO. This enables the engine to operate effectively with a lean fuel mixture. Consequently, the concentration of CO is roughly 20 times lower at its peak when hydrogen is supplemented, in comparison to when no hydrogen supplementation is utilized.

Rahaman et al. [187] conducted an investigation aimed at examining the influence of variations in air–fuel ratio and engine rpm on the operational performance of a singular SI engine, powered by hydrogen. The air–fuel ratio was varied which spanned from the stoichiometric limit to the lean limit, while the rotational speed encompassed a range from 2500 rpm to 4500 rpm. The experiment revealed an increase in both BMEP and BTE. Nonetheless, at elevated air–fuel ratios and rotational speeds, a decline in these parameters was observed. This phenomenon can be attributed to the reduced flammability of hydrogen, as well as its decreased density and reduced air demand for combustion. The volumetric efficiency of the hydrogen-fuelled engine posed a significant challenge, leading to a diminution in power output for each unit volume of hydrogen. Wang et al. [188] and Kiyoshi et al. [189] conducted research that demonstrated the positive impact of hydrogen addition on traditional engines, resulting in enhanced combustion efficiency. This improvement can be attributed to shorter combustion durations, which lead to a greater release of heat occurring closer to the top dead center (TDC) position. D'Andrea et al. [190] conducted a study to explore the impact of varying engine speeds and equivalence ratios on the combustion dynamics within a gasoline engine blended with hydrogen. Their empirical results unveiled a reduction in the duration of combustion and a concurrent increase in nitrogen emissions, correlated with the augmentation of hydrogen blending proportion.

3.6.2. CI engines

In studies focused on hydrogen-fuelled diesel engines, researchers have explored the addition of hydrogen to the diesel fuel through pilot spraying into the cylinder, in addition to using hydrogen as the primary fuel source[191,192]. The dual fuel approach offers significant advantages due to hydrogen's wide ignition ranges and high combustion rate, leading to superior properties in terms of engine performance [193]. Numerous studies have been conducted to investigate the combustion of pure hydrogen in CI engines, as well as the co-combustion of hydrogen-diesel mixtures.

Nag et al. [194] conducted research on the synergistic impact of adding hydrogen and increasing EGR on a diesel-fuelled CI. The authors observed a detrimental effect on both the volumetric efficiency and the EGR system. The study further demonstrated that the levels of CO and CO_2 decreased because of the engine speed. However, the presence of the EGR valve led to a marginal rise in HC emissions due to combustion occurring under low oxygen conditions. Dimitriou et al. [195] conducted emission investigations on dual fuel diesel engines that employed hydrogen as an additional fuel source. The study findings indicate that the EGR valve can effectively regulate the levels of NO_x in the exhaust gases, particularly under medium loads of the diesel engine.

McWilliam et al. [196] investigated the influence of load, speed, EGR level, and hydrogen addition level on the emission characteristics of a diesel engine. They reported that, the introduction of hydrogen in the combustion process resulted in several notable effects. First, the peak cylinder pressure was increased, indicating a higher level of combustion intensity. Additionally, the rate at which the cylinder pressure rises was accelerated. Moreover, as the amount of hydrogen added increased, the position of the peak cylinder pressure was observed to be delayed. These findings, combined with the observed heat release patterns, suggest an increase in ignition delay and a greater proportion of premixed combustion occurring in the engine.

In their study, Masood et al. [170] conducted a comparative analysis of hydrogen-diesel dual fuel combustion and emissions using both the induction and direct injection methods. They concluded that the co-fuelling of hydrogen and diesel can effectively address the limitations associated with lean operation of hydrocarbon fuels like diesel, which are characterized by difficulties in ignition and subsequent reduction in power output. Through the implementation of this co-fuelling approach, the occurrence of misfires is minimized, leading to improved emissions, performance, and fuel economy.

Saravanan and Nagarajan [177] investigated the co-combustion of hydrogen and diesel in a diesel engine. The study involved introducing hydrogen as an enrichment to the diesel fuel, varying the hydrogen content from 10 % to 90 % by volume. The findings of the study indicated that the occurrence of knock was possible when the hydrogen enrichment reached or exceeded 50 % at full engine load. Moreover, the researchers observed lower levels of HC and NO_x emissions in the exhaust gases. They concluded that the optimal enrichment level of hydrogen with diesel fuel was determined to be 30 % based on the examined emission and performance parameters.

Senthil Kumar et al. [197] conducted a study investigating the utilization of hydrogen to enhance the combustion of jatropha oil in a diesel engine. The findings revealed that by incorporating 7 % of hydrogen by mass at the maximum power output, there was an improvement in the BTE, increasing it from 27.3 % to a maximum of 29.3 %. Moreover, a significant reduction in smoke emissions by 20 % was observed. Additionally, at the maximum power output, there was a decrease in the emissions of HC from 130 ppm to 100 ppm, and CO from 0.26 % to 0.17 % (by volume). The optimal mass share of hydrogen was determined to be 7 %. In the case of using diesel fuel, the introduction of 5 % hydrogen by mass resulted in an increase in the brake thermal efficiency from 30.3 % to 32 %. However, when hydrogen was induced, the combustion rates were higher, leading to an increase in NO levels from 735 ppm to 875 ppm at full power output. Furthermore, in the dual-fuel mode of operation, there was an observed increase in ignition delay, peak pressure, and the maximum rate of pressure rise. This was accompanied by a reduction in the duration of combustion due to the accelerated flame speed of hydrogen. Additionally, the introduction of hydrogen induced a higher rate of premixed combustion.

Antunes et al. [198] examined the utilization of hydrogen via direct injection in a naturally aspirated, air-cooled diesel engine with a single cylinder configuration. Their research outcomes indicated that the incorporation of hydrogen direct injection into the diesel engine yielded a more favorable power-to-weight ratio compared to the conventional diesel-fueled operation, resulting in an approximate 14 % increase in peak power output. In order to ensure satisfactory combustion, the hydrogen-fuelled engine required the incorporation of inlet air heating, which led to a significant elevation in the maximum pressure of the gas within the cylinder. Furthermore, a notable efficiency advantage was observed when substituting hydrogen for diesel fuel, with the hydrogen-fuelled engine achieving a fuel efficiency of approximately 43 %, while the conventional diesel-fuelled mode attained only 28 %. Moreover, a reduction of approximately 20 % in the formation of NO_x emissions was noted.

Tsujimura et al. [199] offers an analysis of the auto-ignition characteristics of hydrogen jets in a constant volume vessel. The central focus of their investigation was on the thermodynamic conditions of the surrounding gas, which played a role in influencing the delays experienced before auto-ignition of the hydrogen jets. The researchers concluded that the ambient gas temperature has a substantial effect on the delay before auto-ignition of the hydrogen jet. When the ambient gas temperatures are below approximately 1100 K, the auto-ignition delay displays a linear relationship with temperature when plotted using Arrhenius equation. However, as temperatures exceeded 1100 K, the correlation between temperature and auto-ignition delay weakens, resulting in a plateau value.

Naber and Siebers [200] undertook an examination of the auto-ignition process of hydrogen within conditions simulating diesel combustion. The auto-ignition behaviour of hydrogen was investigated within a controlled-volume combustion vessel. The study explored various parameters, including injection pressure, injection temperature, orifice diameter, as well as ambient gas pressure, temperature, and composition. A robust Arrhenius correlation between ignition delay and temperature was observed, in agreement with the findings of Tsujimura [199]. The impact of the other investigated parameters was deemed insignificant. For gas densities typical of the top dead center (TDC) position in diesel engines, ignition delays of less than 1.0 ms were achieved for gas temperatures exceeding 1120 K. These outcomes affirmed the feasibility of hydrogen compression ignition in a diesel engine under realistic TDC conditions.

Lilik et al. [201] conducted a study to assess the feasibility of replacing diesel fuel with hydrogen in a light-duty diesel engine. Their specific emphasis was on understanding how this substitution could impact exhaust emissions. The researchers systematically introduced varying concentrations of hydrogen into the intake air of the engine, observing significant reductions in NO_x emissions. Nevertheless, it was determined that comparable reductions could also be achieved by manual adjustment of the injection timing. The substitution of hydrogen led to a shift in the NO/NO_2 ratio, with NO_2 becoming the dominant component of NO_x in certain combustion modes. Furthermore, an increase in hydrogen aspiration resulted in a slight rise in PM and HC emissions, while the levels of CO and CO_2 witnessed a decline. The study concluded that hydrogen substitution could potentially replace up to 30 % of the energy derived from diesel fuel required to operate a CI engine under high load conditions, yielding moderate reductions in emissions and having a limited impact on engine performance.

Mansor et al. [202] examined the effects of adding hydrogen and methane to diesel fuel in a direct injection CI engine using computational simulations. The findings indicated that higher diesel content led to a shorter ignition delay but lowered the peak cylinder pressure, whereas, the introduction of methane increased the ignition delay and the formation of CO. On the other hand, hydrogen content increased peak pressure and NO formation. The optimal blend was found to be 70 % hydrogen and 30 % methane with diesel, but higher diesel content was preferable for higher thermal efficiency. The study also showed that the best diesel content was at 60 %, resulting in improved combustion process characteristics and slightly increased combustion emissions.

PM comprises the carbonaceous compounds that result from the incomplete combustion of hydrocarbon fuel. PM is a complex pollutant comprising soluble materials, insoluble materials, and dry fractions [203]. Soot, which falls under the category of insoluble materials, makes up a significant portion of PM (just over 50 %). Particles in PM are found in both liquid phase and agglomerate solid forms. Most liquid phase particles in PM are volatile organic fractions and sulfates sized between 5 and 50 nm. The main constituents of agglomerated particles are soot, organic components (volatile organic fractions or nonvolatile organic fractions), metallic ashes, and SO_4, with a size ranging from 50 to 500 nm [204]. It is important to note that soot agglomerates are mainly formed within the combustion chamber, whereas complex materials (PM) are formed outside the combustion chamber [204].

PM could be reduced by hydrogen enrichment because of the absence of carbon in hydrogen and the reduction in the diesel fuel injection rate [205]. Hydrogen addition to diesel fuel could increase the flame temperature and enhance hydrocarbon combustion, inhibiting PM formation [206].

Ugurlu [207] studied and reviewed the emissions of internal combustion engine (ICE), hybrid, and fuel cell vehicles (FCVs) powered by hydrogen gas or liquid hydrogen. The study compared the well-to-pump (WTP) and well-to-wheel (WTW) emissions of volatile organic compounds (VOCs), CO, NO_x, particulate matter (PM10 and PM2.5), SO_x, and CO_2 from these vehicles for the years 2010, 2020, 2030, 2040, and 2050.

Demir et al. [208] experimentally investigated the impact of using fuel oil graphene and HHO gas addition to diesel fuel on engine performance and exhaust gas emissions. They tested 60 % diesel blended with 40 % fuel oil. HHO gas addition was also added to improve combustion with a flow rate of 5 and 10 lt/min into the intake manifold by using the HHO generator. The operation conditions were used at 3000RPM engine speed at 3.2, 6.4, 7.9, and 12.8 Nm engine torque without any modification on the diesel engine. The experimental results showed that: BSEC, CO, HC, and particle emissions were decreased. Thermal efficiency, NO_x, CO_2, and exhaust gas temperature were increased with the engine torque value increased. As a result of increasing fuel oil addition, Thermal efficiency and CO_2 emission decreased, and BSEC, exhaust gas temperature, HC, CO, NO_x, and particulate emissions were increased. In addition, the thermal efficiency was increased by adding graphene and HHO gas from the intake manifold to fuel oil graphene-diesel blend. Adding HHO gas improved thermal efficiency significantly at the 12.8 Nm engine load. With the addition of graphene and HHO gas to DF40 fuel, the BSEC value was improved at high torque values.

Ozer and Vural [209] studied the addition gases effect of H_2, H_2 + HHO and H_2 + HHO + O_2 from the intake manifold on exhaust emissions in diesel generator using toluene and diethyl ether blend as pilot fuel. The results showed that all exhaust emission values decreased with adding toluene and diethyl ether to diesel fuel, and the tendency to decrease continued even more with the addition of H_2, H_2 + HHO and H_2 + HHO + O_2.

Table 4 summarises the results of different studies fuelled with hydrogen in gasoline or diesel engines.

From the above discussion, the high self-ignition temperature of hydrogen fuel makes it more suitable for gasoline engines than diesel engines. Adding hydrogen to gasoline in certain proportions can increase the compression ratio of the engine, improving its efficiency and performance. Studies have shown that hydrogen enrichment can improve the performance and fuel consumption of gasoline engines, depending on the amount of hydrogen added to the fuel. Additionally, the structural properties of gasoline engines make them more favourable to benefit from hydrogen enrichment in terms of exhaust emissions and fuel consumption rates. On the other hand, due to the high ignition temperature of hydrogen, it is unsuitable for direct use in diesel engines. As a result, researchers have developed various methods to introduce hydrogen into the cylinder. Many studies have shown that adding hydrogen fuel to diesel engines can reduce CO_2 emissions and soot formation in exhaust emissions, but it can also increase NOx emissions. Adding hydrogen to ICE (both SI and CI) reduces volumetric efficiency due to its higher LHV compared to diesel and gasoline. This reduction in volumetric efficiency results in decreased engine power and torque. In addition, the high molecular thermal capacity of hydrogen and the altered combustion process resulting from its addition to internal combustion engines reduce combustion efficiency and BTE in both SI and CI engines. Overall, the majority of ICEs using hydrogen have achieved a reduction in harmful exhaust emissions and fuel consumption.

3.7. Challenges of hydrogen as a fuel

Adapting hydrogen as a fuel for internal combustion engines presents a challenge in managing undesirable combustion events. This stems from hydrogen's intrinsic properties, including its low ignition energy, broad flammability range, and rapid combustion speed, which make it highly susceptible to premature ignition and uncontrolled combustion [218]. The challenge lies in mitigating these undesirable combustion phenomena while maintaining the efficiency and performance benefits of hydrogen as a fuel. This requires careful optimization of engine design, fuel injection strategies, and combustion control mechanisms to tame the reactive nature of hydrogen and harness its energy potential effectively.

3.7.1. Storage challenges

Developing commercially viable hydrogen storage technologies is one of the most significant technical challenges to the widespread adoption of hydrogen as a clean energy carrier [219,220].At present, hydrogen can be stored in five different ways [221]:

High-pressure gas cylinders (up to 800 bar): One of the main hydrogen storage methods is to compress the gas to high pressures, typically in the range of 35–70 MPa. This method is relatively safe and has been used in hydrogen filling stations for decades. However, it has the drawback of requiring heavy and expensive storage tanks. It also reduces the energy density of the hydrogen, making it less efficient to transport over long distances.

Liquid hydrogen in cryogenic tanks (at 21 K): This method allows for a higher storage density, but it requires complex and energy-intensive cryogenic cooling systems. By liquifying the hydrogen, the capacity of the tank increased from 24 g/L at 350 K to 70 g/L at atmospheric pressure and 20 K. Nevertheless, the liquid hydrogen will need to stay at 21 K and that mean very low thermal conductivity for such a tank. These types of tanks are usually made from a double layer of metals with a vacuum gap between the two layers.

Adsorbed hydrogen on materials with a large specific surface area (SSA) (at $T < 100$ K): This method uses porous materials, such as activated carbon or zeolites, to store hydrogen on their surfaces. It has the potential for high storage density, but it is still in the early stages of development.

Absorbed on interstitial sites in a host metal (at ambient pressure and temperature): This method uses metal hydrides to store hydrogen in their crystal structures. It has the potential for high storage density and ambient-temperature operation, but it is also in the early stages of development.

Table 4
Comparative studies fuelled with hydrogen in gasoline or diesel engines.

Author	Fuel %	Operating Conditions	Engine type	Finding
Masood et al. [170]	Dual fuel: Hydrogen & diesel.	• Constant speed of 1400 RPM and load is applied in percentages of full load. • Hydrogen fuel ratio replacement varied from 20 % – 80 % & diesel fuel.	• 4-stroke, single cylinder, compression ignition engine with variable compression ratio. • Dual fuel engine. • CFD & experimental test. • Kirloskar AV-1 engine with DI and inlet manifold. • Compression ratio16.5: 1, variable from 14.3 to 24.5.	• BTE with hydrogen induction > BTE normal operation • Induction NO_x > direct injection NO_x. • Pressure rises and HRR per crank angle: 17 % higher for hydrogen induction than that of direct injection. • NO_x production: 33 % higher for induction compared to that of the injection method at low hydrogen substitution condition.
Dimitriou et al. [195]	Dual fuel: Hydrogen & diesel.	• Constant engine speed of 1,500 rpm. • 20 and 40 kW. • Using various combustion strategies such as:EGR, DIP & diesel injection patterns.	• A 5.2L 4-cylinder heavy-duty CI engine. • Hydrogen (port injection) & diesel (direct injection).	• Carbon emissions ↓ and NO_x emission ↓ for hydrogen addition. • To achieve simultaneous reduction of NO_x, soot, and carbon emissions, water injection and low-temperature combustion techniques is proposed.
Nag et al. [210]	Dual fuel: Hydrogen & diesel.	• Hydrogen fuel ratio: 0 %, 5 %, 10 % & 20 %. • Load of 25 %, 50 % & 75 %. • Constant engine speed 1500 RPM.	• Dual fuel combustion system (Kirloskar, Model TV1). • Single-cylinder, 4-stroke, CI diesel engine.	• Percentage of hydrogen energy share (HES) ↑ • Peak pressure 4.7 %↓ at 25 % & 50 % load conditions and 2 %↑ for 75 % load • Knocking tendency ↓ for hydrogen addition at lower loads and ↑ for higher loads. • Vibrations ↑ for hydrogen addition
Szwaja et al. [211]	Hydrogen fuel. Dual fuel: Hydrogen & diesel.	• Constant engine speed 1500 RPM. • Hydrogen Fuel varying: 0 % to 17 %.	• CI engine. 2-cylinder in-line CI F2L511 manufactured by Deutz under HCCI conditions. • Fixed compression ratio of 17:1. • Diesel fuel was directly injected to the cylinder by a standard six-hole diesel injector. • Hydrogen was delivered by a port fuelled injection (PFI) system containing a hydrogen injector controlled by an electronic control unit (ECU), which adjusted injection timing with accuracy of the engine crankshaft angle of 0.5°	• Diesel ignition lag ↓ for small amounts of hydrogen addition to a diesel engine can Rate of pressure rise ↓ which improves engine durability. • 25 % Hydrogen led to ↑ Combustion knock. • Max hydrogen additions to diesel: not exceeding 15 %.
Tsujimura and Suzuki [212]	Dual fuel: Hydrogen & diesel	• Three engine speed:600, 1000 &1500 RPM. • High engine load.	• 4-stroke water-cooled single cylinder test engine. • Hydrogen (port injection) & diesel fuel (direct injection) • Compression ratio:17.5:1.	• Thermal efficiency of hydrogen diesel dual fuel > Thermal efficiency of conventional diesel operation (under high load). • Limitations due to abnormal combustion • NO_x ↑ as hydrogen fraction ↑.
Jafarmadar [213]	Dual fuel: Hydrogen & diesel	• Constant engine speed of 2600 RPM. • Varies loads. • Hydrogen fuel ratio: 0–100 %. • Using different gas fuel–air ratios: 0.3, 0.4, 0.5, 0.6, 0.7, & 0.8).	• Deutz dual fuel engine F6L912Q.4 S. • CFD & experimental of mixed of Hydrogen & diesel fuel.	• With the increase in the gas fuel–air ratio from 0.3 to 0.8: in-cylinder peak pressure 31.86 %↑, in-cylinder peak temperature 42.28 %↑, cumulative burned fuel exergy 98.2 % ↑ and exergy efficiency ↓ from 43.7 % to 34.5 %. The percentage of exhaust losses exergy ↑ by 51.7 %.
Castro et al. [214]	Dual fuel: Hydrogen & diesel.	• Engine speed: 2400 RPM at 30 %, 60 % & 100 % engine load. • The maximum hydrogen energy substitutions: 80 %, 60 %, & 40 % corresponding to engine loads of 30 %, 60 %, &100 %.	• 4 Cylinder, Perkins Prima M80T Turbocharged & DIE.	• Maximum diesel consumption reduction at 54.2 % compared to 100 % diesel operation at 80 % hydrogen substitution at 30 % load. • Brake fuel conversion efficiency ↓ as hydrogen addition ↑. • The onset of knock occurs with the highest hydrogen energy substitution.
Karagöz et al. [215]	Dual fuel: Hydrogen & diesel.	• Engine speed: 750, 900, 1100,1400,1750 & 2100 RPM. • Hydrogen fuel ratio: 0 %, 25 %, 50 % at full load.	• Ferryman 4-stroke CFR engine.	• Smoke ↓, CO ↓ NO_x ↑ with the addition of hydrogen. • Brake power ↓, brake thermal efficiency ↓, BSFC↓ with hydrogen fraction ↑ • Maximum cylinder pressure ↑ and maximum HRR↑ with hydrogen fraction ↑
Luo and Sun [216]	Dual fuel: hydrogen & gasoline.	Engine speed:1000–6000 RPM.	• 4-cylinder 2.0 L PFI-H_2 ICE.	• Combustion knocks occurrence speed ↑ compared to SI engines. • Factors contributing to combustion knock include ignition timing and backfire. • The initial temperature at ignition is increased owing to backfire
Luo et al. [217]	Hydrogen fuel	• Engine speeds: 1500 RPM to 4000 RPM with interval of 500 RPM. • Engine load: 25 %, 50 %, 75 %. • Equivalence ratio 0.4–1.1	• Turbocharged hydrogen engines, a 2.3 L, 4-St, PFI gasoline engine was converted to a hydrogen engine.	• NO_x emission ↑ as engine speed ↑ & load ↑. • NO_x emission changed from 300 ppm to 1200 ppm with engine speed ↑ & the maximum value reached to 7000 ppm when the equivalence ratio is 0.88 at 2500 rpm &maximum brake torque.

↑increase/lengthen ↓ decrease/shorten; PFI: Port Fuel Injection; DIE: Direct injection engine; ICE: internal combustion engine.

Chemically bonded in covalent and ionic compounds (at ambient pressure): This method uses chemical compounds, such as ammonia or methane, to store hydrogen in their chemical bonds. It has the potential for high storage density and ambient-temperature operation, but it is also in the early stages of development because the end-user either needs to use significant energy to reform the hydrogen from the carrier compound or utilise the carrier compound directly. However, on-board cracking of ammonia to produce even small amounts of hydrogen can create a suitable system because the opposite combustion properties of ammonia and hydrogen can complement each other [222].

The widespread adoption of hydrogen as a fuel for automotive applications hinges on the development of compact, lightweight, affordable, and high energy density storage tanks. Compressed gas storage tanks, commonly constructed from aluminum wrapped with fiberglass, represent a conventional approach. These tanks can store hydrogen at pressures of up to 24.8 MPa and achieve hydrogen capacities of up to 12 kg per cubic meter [223]. However, alternative materials, such as carbon nanotubes, Mg-based alloys, boron compounds, and metal hydrides, have been proposed for hydrogen storage applications. These materials must possess sufficient mechanical strength to withstand the stresses associated with daily hydrogen filling and release cycles. Additionally, they should exhibit high thermal conductivity properties to facilitate rapid heat dissipation from the gas compression process.

3.7.2. Production challenges

In addition to storage challenges, hydrogen production is a significant challenge. The most common method of producing hydrogen is through the SMR process, which involves the reaction of methane with steam to produce hydrogen and carbon dioxide. However, this process is energy-intensive and has a large carbon footprint.

Another method of hydrogen production is through the electrolysis of water, which involves the use of electricity to split water into hydrogen and oxygen. This method is cleaner and more sustainable, but it is currently more expensive than the SMR process and requires significant investments in infrastructure and technology.

Hydrogen can also be produced through biological methods, which involve the use of microorganisms such as algae, bacteria, and yeast to generate hydrogen through a process called biological hydrogen production (BHP). One of the most common BHP methods is to use photosynthetic microorganisms such as algae. These microorganisms use sunlight energy to convert water and carbon dioxide into hydrogen and oxygen through photosynthesis. This method is considered sustainable and renewable because it uses sunlight as the energy source and does not require fossil fuels. Another BHP method is to use fermentative microorganisms such as bacteria and yeast. These microorganisms use organic matter such as sugars and starches as the energy source to produce hydrogen through fermentation. This method is also considered sustainable because it uses organic matter as the energy source and does not require fossil fuels.

BHP has the potential to be a sustainable, renewable, and low-carbon source of hydrogen. Additionally, the organic matter used in fermentation can be derived from biomass such as agricultural and municipal waste, reducing the environmental impact of BHP. However, the efficiency of BHP is still low, and the process is not yet commercially viable. Research and development are ongoing to improve the efficiency of the process and make it more cost-effective and scalable.

Overcoming these challenges will require continued research, development, and collaboration among scientists, engineers, policymakers, and industry partners. As hydrogen technologies mature and costs decrease, hydrogen has the potential to play a significant role in a sustainable energy future.

3.7.3. Leaking hydrogen challenges

Hydrogen leaks can be extremely dangerous and having reliable detection systems in place is an essential safety requirement for the safe handling and use of hydrogen as a fuel. Hydrogen gas is highly flammable and can easily ignite in the presence of an ignition source, making it a potential hazard in any setting where it is used or stored. The rapid mixing of hydrogen with air in the event of a leak or sudden release poses the risk of rapid ignition, potentially resulting in detonation or explosion. Consequently, effective control of hydrogen leaks is imperative to prevent accidents and ensure safety.

Preventing hydrogen leaks in transport vehicles is crucial for safety and environmental reasons. Hydrogen is a highly flammable gas, and leaks can pose a serious risk of explosion and fire. Additionally, hydrogen leaks can contribute to greenhouse gas emissions. To mitigate hydrogen leakage in transport vehicles, several critical measures should be implemented:

Leak-proof components and seals: Employ high-quality, durable components and seals specifically designed for hydrogen applications. These components should be able to withstand the high pressures and temperatures associated with hydrogen storage and transportation.

Regular inspections and maintenance: Implement a rigorous inspection and maintenance schedule for hydrogen fuel systems. This should include regular checks for leaks, corrosion, and damage to components.

Leak detection systems: Install reliable leak detection systems that can quickly and accurately detect hydrogen leaks. These systems should be capable of alerting the driver or control system of a leak, allowing for timely intervention.

Emergency shut-off valves: Equip hydrogen fuel systems with emergency shut-off valves that can rapidly isolate the hydrogen supply in the event of a leak. These valves should be strategically located and easily accessible for manual or automated operation.

Hydrogen Venting Systems: Design and implement hydrogen venting systems to safely release hydrogen away from populated areas and potential ignition sources. Venting systems should be designed to minimize the environmental impact of the released hydrogen.

Robust hydrogen storage tanks: Utilize robust hydrogen storage tanks that comply with safety regulations and industry standards. These tanks should be designed to withstand the pressures and temperatures associated with hydrogen storage and transportation.

Safe hydrogen fueling stations: Implement stringent safety protocols and procedures at hydrogen fueling stations to minimize the risk of leaks during refueling. This includes proper training for station personnel, leak detection systems, and emergency response plans.

Emergency Response Plans: Develop and implement comprehensive emergency response plans that outline procedures for leak detection, isolation, evacuation, and firefighting in the event of a hydrogen leak.

By implementing these measures, we can significantly reduce the risk of hydrogen leaks in transport vehicles, ensuring the safe and sustainable utilization of hydrogen as a clean energy source. Ensuring the safety of hydrogen leaking from a ruptured pipe requires a comprehensive approach that encompasses prevention, detection, and mitigation strategies [224,225].

In Canada, the government has developed safe work procedures for dealing with hydrogen as a fuel. These procedures outline the steps that must be taken to ensure the safe handling and use of hydrogen, including the proper storage and handling of the gas, as well as the use of appropriate safety equipment and procedures to prevent leaks and minimize the risk of fire and explosion.

One of the key safety requirements outlined in these procedures is the use of reliable detection systems to detect hydrogen leaks. These systems are designed to detect the presence of hydrogen gas in the event of a leak and can be configured to trigger an alarm or shut off the gas supply to prevent a potential fire or explosion [226].

Detection systems can be of different types, including gas sensors, infrared cameras, acoustic sensors, and optical sensors. These systems are sensitive enough to detect even small amounts of hydrogen gas and are designed to operate in a wide range of conditions, including extreme temperatures and high humidity.

In addition to detection systems, other important safety measures that are outlined in the Canadian government's safe work procedures for hydrogen include the use of proper ventilation systems, the use of protective equipment such as face masks and gloves, and the training of employees to recognize the signs of a hydrogen leak and take appropriate actions to prevent injury or damage.

3.7.4. Recoil (knock) in hydrogen engines

The recoil process, also known as knock, is a major challenge in hydrogen engines due to the high reactivity and low ignition energy of hydrogen [218]. This can lead to uncontrolled combustion, damaging the engine and reducing its efficiency. Several approaches are being explored to address the recoil process in hydrogen engines:

- Engine design modifications: Optimizing the engine's combustion chamber geometry, compression ratio, and fuel injection strategy can help mitigate the occurrence of knock. This may involve using smaller chambers, lower compression ratios, and multi-stage injection to control the combustion process.
- EGR: Introducing inert exhaust gases into the intake mixture can reduce the combustion temperature and slow down the flame propagation, thereby suppressing knock. EGR systems need to be carefully controlled to maintain engine performance and emissions.
- Variable valve timing (VVT): Adjusting the timing of the intake and exhaust valves can influence the combustion process and reduce knock tendency. VVT systems can dynamically adapt to changing engine conditions and fuel mixtures.
- Fuel additives: Adding certain compounds to the hydrogen fuel can modify its combustion characteristics and reduce knock. These additives may act as inhibitors or act as coolants to reduce the combustion temperature.
- Catalytic combustion: Employing a catalyst to promote controlled combustion of hydrogen can help prevent knock by controlling the reaction rate and preventing uncontrolled ignition. Catalytic combustion systems are still under development for hydrogen engines.
- Hydrogen-rich blends: Blending hydrogen with other fuels, such as natural gas or methane, can lower the overall reactivity of the fuel mixture and reduce knock tendency. However, this approach may compromise the energy density and efficiency of the fuel.
- Laser ignition: Using lasers to initiate combustion with high precision and control can help prevent knock by igniting the fuel at multiple points simultaneously, leading to a more uniform and controlled combustion process.
- Plasma-assisted ignition: Plasma ignition systems can generate a localized plasma discharge to initiate combustion, offering precise control over the ignition process and reducing knock tendency.
- Advanced combustion concepts: Exploring alternative combustion modes, such as stratified charge combustion or lean-burn combustion, may offer ways to suppress knock while maintaining engine efficiency.
- Knock detection and control systems: Developing robust knock detection systems and control strategies is crucial to identify and mitigate knock events in real-time. These systems can adjust engine parameters, such as ignition timing or fuel mixture, to prevent knock from occurring.

Addressing the recoil process in hydrogen engines requires a combination of hardware and software advancements. By optimizing engine design, utilizing advanced combustion techniques, and implementing effective knock detection and control systems, researchers are paving the way for more efficient and reliable hydrogen engines.

3.7.5. Backfire (flashback) in hydrogen engines

Backfire, also known as flashback, is an undesirable phenomenon that can occur in hydrogen engines when the flame prematurely propagates back into the intake manifold or air intake system [218]. Backfire, characterized by combustion and pressure surges within the intake manifold, manifests as audible noise and can potentially cause damage or destruction to the intake system. Hydrogen's wide flammability range, which spans 4 % to 75 % by volume in air [227,228], means that hydrogen is more susceptible to ignition than fuels with narrower flammability limits. Additionally, hydrogen has a low ignition energy threshold [229], meaning that it can be ignited by even low-energy sources such as sparks or hot surfaces. Laminar flame speed of hydrogen is also much higher compared to other discussed fuels [230,231]. All these factors are demonstrated to have a close relationship with backfire occurrences. As a result, minimizing ignition sources is a critical safety consideration when working with hydrogen. Finally, quenching distance of hydrogen is much smaller contributing to easier burning around the walls and in crevices under normal operation conditions [232,233]. The shockwave from a hydrogen detonation can propagate at very high speeds, causing significant damage to structures and equipment [234]. Therefore, it is essential to manage and mitigate the risks associated with backfire in any project involving hydrogen.

Several factors can contribute to backfire in hydrogen engines:

- Lean air–fuel mixture: A lean air–fuel mixture, where there is not enough hydrogen to complete combustion, can lead to slow flame propagation and increased susceptibility to backfire.
- Early ignition: Early ignition, when the spark occurs before the optimal time, can cause the flame to propagate too quickly, increasing the risk of backfire.
- Intake manifold design: The design of the intake manifold can influence the flow of the air–fuel mixture and affect the likelihood of backfire.
- Intake valve timing: The timing of the intake valves can impact the mixing of hydrogen and air and influence the flame propagation process.
- Engine operating conditions: Factors such as engine load, speed, and temperature can also influence the occurrence of backfire.

To prevent backfire in hydrogen engines, several strategies can be employed:

- Optimizing ignition timing: Precise ignition timing is crucial to ensure that the flame propagates at a controlled rate, minimizing the likelihood of backfire.
- Enhancing intake manifold design: Designing intake manifolds that promote uniform mixing of hydrogen and air and optimize gas flow can help prevent backfire.
- Refining intake valve timing: Optimizing intake valve timing can control the timing of air introduction into the combustion chamber, influencing flame propagation and reducing backfire risk.
- Controlling engine operating conditions: Monitoring and regulating engine parameters such as load, speed, and temperature can help maintain stable combustion conditions and minimize backfire occurrences.

3.7.6. Hydrogen power density challenges

The low power density of hydrogen by volume compared to other fuels such as gasoline or NG further underscores the challenges associated with its use as a fuel source [235]. This means that to meet the same energy requirements, hydrogen must be stored in a larger volume, which can impact storage and transportation logistics. To achieve a reasonable energy density for certain applications, hydrogen must be stored at very low temperatures using cryogenic storage techniques. This requires specialized equipment and insulation, adding to the complexity and cost of hydrogen infrastructure. Alternatively, hydrogen can be compressed to increase its energy density, but this requires high-pressure storage tanks that must be carefully designed and maintained to ensure safety. Additionally, hydrogen can embrittle certain materials [236], which can compromise the structural integrity of storage and transportation systems. Therefore, ensuring material compatibility with hydrogen is essential. Furthermore, when hydrogen is used in fuel cells to generate electricity, energy losses occur during the conversion process, further reducing the overall power density of hydrogen-based systems [237].

3.7.7. Corrosion of engine parts

Hydrogen is a highly reactive gas that can cause corrosion in a variety of engine parts while its low density presents difficulties in fuel injection systems[238,239], including:

- Cylinder heads: Hydrogen can react with the aluminum or cast iron in cylinder heads to form aluminum hydride or iron hydride, respectively. These hydrides are brittle and can crack, leading to leaks and engine failure.
- Piston rings: Hydrogen can diffuse into piston rings and cause them to swell and become brittle. This can lead to ring breakage and loss of compression.
- Valves: Hydrogen can react with the steel in valves to form hydrogen embrittlement. This is a condition that makes the steel brittle and susceptible to cracking.
- Turbines: Hydrogen can react with the nickel or cobalt in turbine blades to form hydrides. These hydrides can cause the blades to become brittle and crack.

There are a number of ways to protect engine parts from hydrogen corrosion, including:

- Using corrosion-resistant materials: This is the most effective way to protect engine parts from hydrogen corrosion. However, corrosion-resistant materials can be more expensive than traditional materials.
- Applying protective coatings: Protective coatings can be applied to engine parts to prevent hydrogen from diffusing into the metal. However, coatings can be damaged over time, and they may not be effective in all environments.
- Using hydrogen scavengers: Hydrogen scavengers are chemicals that can react with hydrogen to form harmless compounds. This can help to reduce the concentration of hydrogen in the fuel or oil.

To prevent hydrogen corrosion in engine parts, special materials needs to be employed for engine components that are exposed to high temperatures and pressures. Additionally, corrosion-resistant materials are utilised for components exposed to hydrogen to mitigate the potential effects of corrosion [225,240,241]. It is advisable to use high-quality fuel and oil with low sulfur and minimal contaminants. Regularly changing the oil and filter in accordance with the manufacturer's recommendations is essential. Maintaining proper engine cooling and ventilation is crucial, while avoiding excessive idling helps mitigate the risk of hydrogen-related corrosion. These practices collectively contribute to the preservation of engine components and the prevention of potential damage associated with hydrogen exposure. It is important to monitor engine parts for signs of hydrogen corrosion. This can be done by performing regular inspections and by analyzing oil samples. If hydrogen corrosion is detected, the affected parts should be replaced immediately.

Hydrogen is a versatile fuel source with both valuable and challenging properties, especially when considering detonation and power density. One key challenge is hydrogen's high flame speed compared to other fuels [242]. This means that a leak or sudden release of hydrogen can rapidly mix with air and ignite, potentially leading to a detonation or explosion. Therefore, controlling hydrogen leaks is essential to prevent accidents. Another challenge is hydrogen's wide flammability range, which spans 4 % to 75 % by volume in air [227,228]. This means that hydrogen is more susceptible to ignition than fuels with narrower flammability limits. Additionally, hydrogen has a low ignition energy threshold [229], meaning that it can be ignited by even low-energy sources such as sparks or hot surfaces. As a result, minimizing ignition sources is a critical safety consideration when working with hydrogen. Finally, the shockwave from a hydrogen detonation can propagate at very high speeds, causing significant damage to structures and equipment [234]. Therefore, it is essential to manage and mitigate the risks associated with detonation in any project involving hydrogen.

The low power density of hydrogen by volume compared to other fuels such as gasoline or NG further underscores the challenges associated with its use as a fuel source [235]. This means that to meet the same energy requirements, hydrogen must be stored in a larger volume, which can impact storage and transportation logistics. To achieve a reasonable energy density for certain applications, hydrogen must be stored at very low temperatures using cryogenic storage techniques. This requires specialized equipment and insulation, adding to the complexity and cost of hydrogen infrastructure. Alternatively, hydrogen can be compressed to increase its energy density, but this requires high-pressure storage tanks that must be carefully designed and maintained to ensure safety. Additionally, hydrogen can embrittle certain materials [236], which can compromise the structural integrity of storage and transportation systems. Therefore, ensuring material compatibility with hydrogen is essential. Furthermore, when hydrogen is used in fuel cells to generate electricity, energy losses occur during the conversion process, further reducing the overall power density of hydrogen-based systems [237].

To conclude, the utilisation of hydrogen combustion in IC engines holds significant potential as a sustainable and environmentally friendly fuel. However, this technology also presents certain challenges pertaining to engine materials. The high temperatures and pressures associated with hydrogen combustion can result in wear and damage to engine components. Furthermore, the reactivity of hydrogen poses a risk of corrosion, while its low density presents difficulties in fuel injection systems. To overcome these challenges, special materials are employed for engine components that are exposed to high temperatures and pressures. Additionally, corrosion-resistant materials are utilised for components exposed to hydrogen to mitigate the potential effects of corrosion [225,240,241].

4. Conclusion

Given the increasing concerns about the environment and energy, NG has emerged as a promising alternative fuel. Natural gas/diesel dual fuel mode is a more practical and cost-effective way to use NG in diesel engines. This method has attracted significant attention from researchers seeking to improve engine performance and reduce diesel consumption. In SI engines, NG fuel properties have a clear and direct positive effect on fuel economy and some emissions, such as CO_2 and non-methane hydrocarbons. However, the effects on other emissions, such as unburnt HC, NO_x, and CO, are less clear. NG has lower NO_x emissions due to a lower adiabatic flame temperature than diesel fuel. DI NG engines also emit less PM mass than diesel engines, especially at high EGR levels. Burning NG also produces less CO_2 than burning diesel fuel for the same amount of energy released. However, NG combustion in an IC engine is not as complete as diesel fuel combustion for the same operating condition due to its slower burning rate. This results in higher unburnt HC emissions from a DI NG engine than from a diesel engine. CNG DI combustion achieves shorter combustion duration and comparable combustion efficiency to homogeneous mixture combustion. However, NO_x emissions are high, while CO emissions remain low. In dual fuel (DF) engines, the in-cylinder pressure during compression and the early stage of combustion is slightly lower than in diesel engines, and the ignition delay is longer. The peak in-cylinder pressure, pressure rise rate, and heat release rate under DF mode are all strongly correlated with the pilot diesel injection parameters. Increasing the amount of pilot diesel injected can extend the lean burn limit and reduce HC and CO emissions, but it has the opposite effect on NO_x emissions.

The high self-ignition temperature of hydrogen fuel makes it a more suitable additive for gasoline engines than for diesel engines. Adding hydrogen to gasoline in certain proportions can permit increases in the compression ratio of the engine, improving its efficiency and performance. Studies have shown that hydrogen enrichment can improve the performance and fuel consumption of gasoline engines, depending on the amount of hydrogen added to the fuel. Additionally, the structural properties of gasoline engines make them more compatible with hydrogen enrichment, resulting in reduced exhaust emissions and fuel consumption rates. In contrast, hydrogen's high ignition temperature makes it unsuitable for direct use in diesel engines. Consequently, researchers have developed various methods to introduce hydrogen into the cylinder. Many studies have shown that adding hydrogen fuel to diesel engines can reduce CO_2 emissions and soot formation in exhaust emissions, but it can also increase NO_x emissions. Nevertheless, the majority of internal combustion engines using hydrogen have achieved a reduction in harmful exhaust emissions and fuel consumption.

Despite the promising results obtained to date, further research is needed to fully understand the impact of hydrogen fuel on different engine types. Despite these challenges, hydrogen is a sustainable and ecologically favorable energy source that warrants wider implementation, notwithstanding the significant barrier posed by its cost, which hinders widespread adoption. Effectively addressing the challenges of implementing hydrogen as a fuel requires a holistic approach that encompasses careful engineering, rigorous safety measures, and ongoing technological advancements. Researchers and engineers should work diligently to improve the safety and efficiency of hydrogen systems, making them more viable for a wide range of applications, including clean energy production and transportation.

CRediT authorship contribution statement

Sattar Jabbar Murad Algayyim: Writing – review & editing, Writing – original draft, Resources, Methodology. **Khalid Saleh:** Writing – review & editing, Writing – original draft, Methodology. **Andrew P. Wandel:** Writing – review & editing, Supervision. **Islam Md Rizwanul Fattah:** Writing – review & editing, Writing – original draft, Methodology. **Talal Yusaf:** Writing – review & editing, Methodology. **Hayder A. Alrazen:** Writing – review & editing, Resources, Methodology.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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