Article citation info:
Nieścioruk MJ, Boroiu A-A, Onescu C, Ozuna G, Ávila AB, Kubiak P et al. The use of hydrogen to supply combustion engines – part 2. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-214622

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The use of hydrogen to supply combustion engines – part 2

ARTICLE INFO

Received: 28 April 2025
Revised: 6 October 2025
Accepted: 23 November 2025
Available online: 14 January 2026

The present study reviews the state-of-art regarding the application of H_2 in the automotive industry. This part focuses on dual-fuel (DF) internal combustion engines (ICEs) supplied with fuel and H_2. This is a continuation of the earlier part, which focused on out-of-engine studies on the effect of H_2 combustion processes, ICEs supplied with H_2, and vehicles powered by fuel cells (FCs). Using H_2 in diesel engines via the DF strategy enables a decrease in diesel fuel consumption and a reduction in harmful exhaust emissions. Using H_2 in diesel engines powered by diesel/biodiesel mixtures also allows for reducing reliance on fossil fuels. Also, incorporating nanomaterials or oxygen-containing compounds into diesel fuel formulations may enhance the combustion efficiency of H_2-powered diesel engines, thereby increasing thermal efficiency and reducing fuel consumption. However, additional studies are required on this subject.

Key words: *hydrogen, dual-fuel engine, combustion engine, emission*

1. Introduction

Nowadays, hydrogen (H_2) is increasingly used to power internal combustion engines (ICEs) in both mobile and stationary applications. Developments in the transport and energy sectors have heightened interest in using fuels derived from renewable sources rather than fossil ones.

The present study reviews the state-of-art in the application of H_2 in the automotive industry. This part focuses on dual-fuel (DF) ICEs supplied with conventional fuel and H_2 and continues the earlier part that examined out-of-engine H_2 combustion studies, ICEs operating solely on H_2, and vehicles powered by fuel cells (FCs).

2. Dual-fuel combustion engines supplied with conventional fuel and hydrogen

According to [8], in case of a gas shortage, DF ICEs can operate on gaseous fuel with a diesel pilot or solely on diesel. Converting an existing diesel ICE to dual-fuel operation is relatively straightforward and requires only minor modifications. Because of the excellent anti-knock properties of H_2, the original cylinder geometry can be retained and the compression ratio (CR) preserved.

According to [17], DF ICEs are recommended when using H_2-enriched compressed natural gas (HCNG) with an H_2 mass fraction of 0–50%; when NH_3 or pure H_2 is used, compression-ignition (CI) ICEs are preferable for environmental reasons.

Several studies have confirmed the positive role of exhaust-gas recirculation (EGR) in DF ICEs fueled with conventional fuel and H_2.

Purayil et al. [70] observed that H_2–gasoline DF ICEs use H_2 as the main fuel and gasoline as the auxiliary fuel. Such engines exhibit high thermal efficiency at low and partial loads, but their power output declines at high loads. The optimal configuration combines H_2 direct injection with gasoline port-fuel injection (PFI), which mitigates abnormal combustion but increases emissions. Using EGR reduced emissions by up to 77.8% at an EGR rate of 18%; higher rates, however, induced combustion instability.

Alrazen et al. [3] reported that the air–fuel (A/F) ratio, engine speed and load significantly influence the performance and emissions of diesel ICEs enriched with H_2. Brake thermal efficiency (BTE), brake power (BP), brake mean effective pressure (BMEP), and specific energy consumption (SEC) all depend on operating conditions when H_2 is introduced. Increasing the H_2 fraction decreases unburned hydrocarbons (UHCs), CO, CO_2, particulate matter (PM), and smoke, whereas NO_x rises; this increase can be controlled through injection strategies, EGR, water injection, or exhaust after-treatment.

Banerjee et al. [9] reported that initiating H_2 dual-fuel combustion with a diesel pilot improves conventional diesel performance while reducing regulated emissions, even though H_2 enrichment tends to raise NO_x. Because H_2 has a wide flammability range, high diffusivity, and low ignition energy, DF combustion tolerates higher EGR rates than conventional diesel. Extensive EGR alleviates NO_x–PM trade-offs without compromising performance and can obviate complex NO_x after-treatment.

Dimitriou and Tsujimura [27] demonstrated that the use of H_2 in compression ignition (CI) engines markedly reduces HC, CO, CO_2, and smoke – often by more than 50% under optimal conditions. Higher H_2 fractions raise the heat-release rate and BTE but also elevate in-cylinder temperature, sharply increasing NO_x, especially at high loads. EGR reduces NO_x in proportion to the EGR rate but may raise smoke, CO, and HC owing to lower O_2. Combining H_2 with optimized EGR simultaneously cuts all emissions relative to pure diesel operation, yet NO_x remains the principal challenge.

Rosha et al. [74] reviewed many studies on H_2 addition to diesel or biodiesel (BD) pilots in DF CI ICEs and concluded that:

- H_2's higher laminar flame speed, shorter ignition delay, and lower minimum ignition energy accelerate flame propagation and kernel development
- BTE and BP generally improve with greater H_2 energy share owing to shorter combustion duration, higher heat-release rate, and higher peak pressure; however, knocking increases, BMEP falls in fuel-rich mode, and rises modestly under lean burn
- Because H_2 is carbon-free, CO, CO_2, and HC emissions fall at all loads, whereas NO_x increases due to higher temperature.

Arjun et al. [7] reported that the addition of Brown (HHO) gas, a mixture of H_2 and O_2 produced by electrolysis, to ICEs raised BP by 2–5.7% and BTE by 10.3–34.9%, reduced brake-specific fuel consumption (BSFC) by 20–30%, and cut CO and HC by 18% and 14%, respectively. NO_x responses varied among studies.

Thiyagarajan et al. [96] investigated H_2 addition to various BD/vegetable oils on CI ICE performance. BTE, BSFC, in-cylinder pressure and heat release rate, as well as UHCs, CO, NO_x, and smoke emissions, were thoroughly assessed. H_2 inclusion generally enhances ICE performance compared to BD/vegetable oil, though it remains comparable to or lower than diesel. H_2 addition improved BTE and fuel efficiency in CI ICEs, regardless of the fuel type utilized. This results from the higher heating value and faster combustion characteristics of H_2. H_2 combustion enhances burning efficiency, leading to higher heat release rates and maximum pressures. The high auto-ignition temperature of H_2 limits its exclusive use in CI ICEs. H_2 can serve as fuel in CI ICEs alongside pilot fuel, with the knock limitation for H_2 being approximately 20%. All emissions, except NO_x, exhibited a downward trend with H_2 inclusion. H_2 significantly reduces CO_2 emissions based on the carbon content in the molecular structure of BD or vegetable oil. Since H_2 is carbon-free, emissions of HC, CO, and smoke are consequently reduced. However, the decrease depends solely on the quantity of H_2 introduced and the type of fuel used. H_2 combustion increases NO_x emissions regardless of the fuel type used. To mitigate this effect, various after-treatment systems, such as selective catalytic reduction (SCR), exhaust gas recirculation (EGR), selective non-catalytic reduction (SNCR), and non-selective catalytic reduction (NSCR), have been suggested.

Following an extensive analysis of HHO production through various generators and its application in heating and power contexts, Paparao and Murugan [68] found that HHO can serve as an alternative fuel in SI ICEs either independently or in combination with gasoline or similar fuels. Thermal efficiency increased while BSFC decreased with HHO use in SI ICEs. CO, HC, and CO_2 emissions decreased in SI ICEs powered by HHO fuel throughout the entire operating range. Furthermore, gaseous HHO can be utilized in CI ICEs operating in dual-fuel (DF) configuration. When HHO was employed in CI ICEs in DF mode, BTE improved and BSFC decreased. CO, HC, and smoke emissions decreased, while NO_x increased throughout the entire ICE operating range.

When examining various efficiency reports and emission characteristics of CI ICEs powered by HHO, Ridhuan et al. [4] discovered that HHO gas enhanced brake power (BP) and torque. In all cases, an improvement in brake thermal efficiency was observed. This was because HHO gas contains H_2, which has a higher calorific value than fossil fuels. Simultaneously, BSFC was reduced, and the combined effects of H_2 and oxygen facilitated complete combustion, enhancing combustion efficiency when HHO gas was introduced. HHO gas inclusion improved BP, brake torque (BT), and BTE while reducing BSFC and lowering CO and HC emissions. The increase in CO_2 emissions indicated complete combustion. Consequently, utilizing HHO gas in CI ICEs improved ICE efficiency and reduced exhaust emissions.

Hosseini et al. [38] reported that HHO enrichment serves as a practical solution to enhance diesel ICE performance while minimizing exhaust emissions. HHO also addresses storage and safety concerns associated with H_2 use in diesel ICEs. HHO can boost BTE of diesel ICEs and reduce BSFC by increasing the calorific value of air-fuel (A/F) mixtures and improving combustion efficiency. HHO addition can enhance heat release rates and in-cylinder pressure of diesel ICEs due to increased flame speed and diffusivity of monoatomic H_2. HHO inclusion in diesel fuel may reduce ignition delays by creating a uniform air-fuel mixture. HHO incorporation may lead to notable decreases in CO, CO_2, UHC, smoke, and particulate matter (PM) emissions from diesel ICEs. This effect may be attributed to the presence of H_2 and oxygen in carbon-free HHO, which accelerates fuel oxidation processes and ensures complete combustion. HHO gas may successfully address the negative impacts of adding gaseous fuel to diesel fuel, such as reduced efficiency metrics and increased CO and UHC emissions.

Akal et al. [2] evaluated H_2 application as a fuel for vehicles and as an additional fuel source. They discovered that due to the elevated self-ignition temperature of H_2 fuel, it is better suited for use in gasoline ICEs. Incorporating H_2 into gasoline in specific ratios can further increase compression ratios (CRs), enhancing ICE efficiency and performance. In numerous studies, depending on the quantity of H_2 incorporated into fuel, ICEs have demonstrated improvements in both performance and fuel efficiency. Moreover, due to the structural characteristics of ICEs, gasoline ICEs are better positioned to utilize H_2 enrichment in terms of emissions and BSFC levels. When H_2 fuel was added to the LPG ICEs, there was a slight decrease in torque and power. When the quantity of H_2 supplied to the LPG system was increased, the BSFC and harmful emissions from these ICEs decreased. However, gaseous fuels and H_2 fuel reduce volumetric efficiency since they occupy more space in the ICE cylinder compared to gasoline. This can be addressed by designing various combustion chambers, increasing the cylinder capacities of ICEs that will utilize H_2 fuel, and incorporating variable valve timing and different valve designs. In diesel ICEs, different outcomes were noted based on the quantity of H_2 added to the fuel and the ICE speed. Although the torque and power outputs of certain ICEs increased with H_2 utilization, other ICEs experienced a decline in torque and power values as speeds increased. Due to H_2's elevated ignition temperature, it is unsuitable for direct application in diesel ICEs. Consequently, in numerous studies, various techniques were employed to inject H_2 into the cylinder. In various studies where H_2 fuel was added to diesel ICEs, a reduction in CO_2 emissions and soot production in exhaust emissions was noted, although an enhancement in NO_x emissions was also recorded. Many ICEs utilizing H_2 achieved reduced BSFC and harmful exhaust emissions.

Wang et al. [104] noted that H_2 fuel is beneficial as a fuel for automotive ICEs due to its advantages of wide flammability limits and high flame speed. Its introduction can significantly enhance the combustion and emission properties of ICEs. Regardless of ICE type, efficiency can be enhanced through targeted H_2 doping methods and specific H_2 doping ratios. Nevertheless, the optimal mode and proportion vary based on operating conditions. The performance of H_2 ICEs and H_2 blended ICEs is highly influenced by H_2 injector positions and H_2 injection control strategies.

Deheri et al. [22] noted that H_2, as a fuel with higher flame speed and lower ignition energy, enhances peak cylinder pressure and heat release rate. H_2 use as a fuel cause knocking in CI ICEs and increases NO_x emissions due to its rapid flame propagation. Combustion parameters like maximum in-cylinder pressure and heat release rate can be enhanced by up to 30%, while combustion duration and ignition delay can be reduced by 4 to 5%, by introducing biogas (BG) and H_2 into the cylinder alongside advanced injection timing and increased CRs. Diethyl Ether (DEE) serves as a beneficial additive alongside these alternative fuels to enhance combustion properties. DF mode reduced NO_x and smoke emissions by up to 60%, while HC and CO emissions may increase by up to 30%. However, these emissions can be controlled by employing control techniques and adding additional components with the pilot fuel.

Das et al. [19] also reported that H_2 in producer gas (PG) is the key element affecting ICE performance. A higher percentage of H_2 in producer gas enhances combustion efficiency and peak cylinder pressure (PCP). Nevertheless, a higher amount of inert gases, such as CO_2 and N_2, in PG inhibits pre-flame development that leads to knocking. Incomplete combustion during DF mode led to increased emissions of HC and CO compared to diesel mode. Utilizing BD as a pilot fuel enhances combustion efficiency of both gaseous and liquid fuels by supplying adequate O_2, leading to decreased levels of HC and CO. Moreover, H_2 incorporation in PG decreases the amount of carbon particles in the fuel and increases the average gas temperature, thereby reducing CO. Regarding producer gas use, a higher quantity of H_2 increases NO_x emissions.

H_2 use in diesel ICEs does not necessarily require significant modifications to the internal combustion engine (ICE). In their comprehensive review, Hosseini et al. [38] explained that H_2 can be utilized in existing CI diesel ICEs in DF configurations with minor adjustments. The specific physicochemical traits of H_2, including its higher calorific value, flame speed, and diffusivity, can significantly enhance the efficiency and combustion properties of diesel ICEs. Being a carbon-free fuel, H_2 can also reduce harmful emissions from diesel ICEs, such as CO, UHC, PM, soot, and smoke. Nevertheless, diesel ICEs running on H_2 experience knocking combustion and elevated NO_x emissions. This review thoroughly examines the impact of H_2 or gaseous fuels containing H_2 (such as syngas (SG) and HHO gas) on the performance of DF diesel ICEs. H_2 can effectively decrease all carbonaceous emissions from diesel ICEs. Real-time H_2 injection control can eliminate its disadvantages in diesel ICEs. H_2 cannot enhance all performance metrics and exhaust emissions of diesel ICEs simultaneously. Nevertheless, modifying pilot fuel through additives, mixing H_2 with other gaseous fuels, changing ICE settings, improving operational conditions, adapting ICE design, utilizing HHO gas, and implementing exhaust gas catalysts may facilitate the development of safe, efficient, and cost-effective H_2-powered diesel ICEs.

H_2 inclusion in diesel fuel may enhance the BTE of diesel ICEs and reduce the BSFC rates. This may result from the increased heating value and faster burning of gaseous H_2. H_2 might also offset the reduced calorific value of BD while addressing its primary limitations, such as decreased BTE and increased BSFC. Increased H_2 addition levels may enable more uniform charge combustion, resulting in improved combustion characteristics. However, introducing H_2 above a specific threshold, especially under high ICE loads, could lead to knocking issues. The H_2 inclusion rate that results in knocking varies among ICEs, fuels, and operating conditions. Thus, a definitive guideline for the optimal H_2 inclusion rate cannot be established [38].

Selected characteristics of DF ICEs powered by diesel fuel, reviewed by Hosseini et al. [38], are shown in Fig. 1. The studied ICEs operated at speeds with a mean value of 1724 rpm and a standard deviation (SD) of 528. The displacement of such ICEs had a mean value of 1674 cm^3 and a high SD of 2325 cm^3. ICE minimum loads reached the mean value of 27.3% and SD of 34%, while maximum loads reached the mean value of 82% and SD of 32%. ICE load can vary between 0 and 100%. The ICE's minimum CR reached a mean value of 16.41 and SD of 4.72, while the maximum CR reached a mean value of 16.49 and SD of 4.78.

The effect of load, EGR and H_2 supply on BTE and BSFC for DF ICEs ignited by diesel fuel is shown in Fig. 2. For the data presented in Fig. 2a, 16% and approximately 65% of the analyzed cases exhibited missing data for BTE and BSFC, respectively. 13.5% showed reductions, approximately 3% and none showed no effect, and about 68% and 21.6%, respectively, showed increases. For the data presented in Fig. 2b, 28.5% and 71.4% of the analyzed cases exhibited missing data for BTE and BSFC, respectively. No cases showed reductions or no effects, and approximately 71.5% and 58.6%, respectively, showed increases. For data in Fig. 2c, 25% and 87.5% of analyzed cases exhibited missing data for BTE and BSFC, respectively; 12.5% and none showed reductions, no cases showed no effect; and about 62.5% and 12.5%, respectively, showed increases.

Integrating H_2 into pure diesel fuel may enhance the BTE of diesel ICEs [37, 46, 71, 72]. Incorporating H_2 into pure diesel fuel can result in a more complete combustion process due to its higher flame temperature and faster flame speed compared to conventional diesel [35, 47, 62, 112].

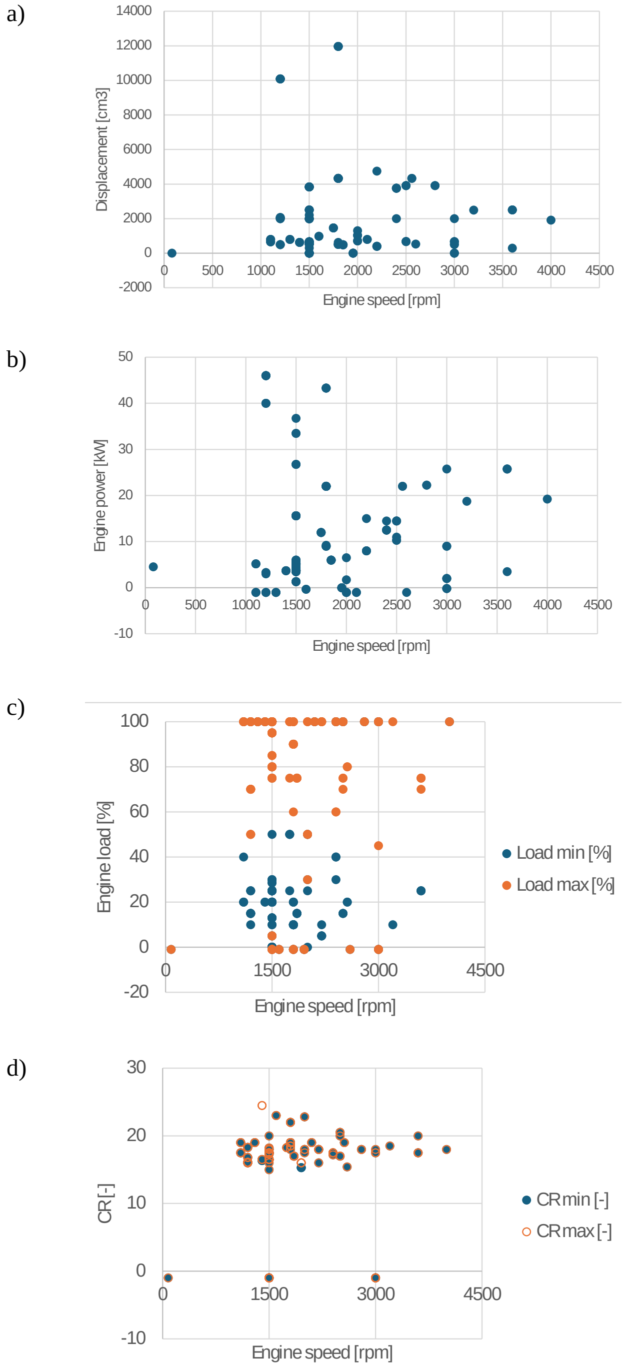

Fig. 1. Selected characteristics of DF ICEs ignited by diesel fuel speed (negative values correspond to missing data); a) displacement versus ICE speed, b) ICE power from 1-cylinder versus ICE, c) ICE load versus ICE speed, d) ICE CR versus ICE speed based on data from [38]

H_2 can improve the combustion of diesel fuel because its premixed flames possess wider flammability limits than hydrocarbon fuels, thereby enhancing the BTE of diesel ICEs [78]. H_2 can also shift the peak heat release closer to the injection (TDC) point, resulting in improved cycle efficiency of diesel ICEs [78]. Nonetheless, utilizing H_2 in a diesel ICE does not always guarantee an improvement in BTE. Although H_2 has higher energy content per unit mass compared to diesel fuel, factors such as the air-fuel (A/F) ratio and ICE design can significantly affect BTE. A factor

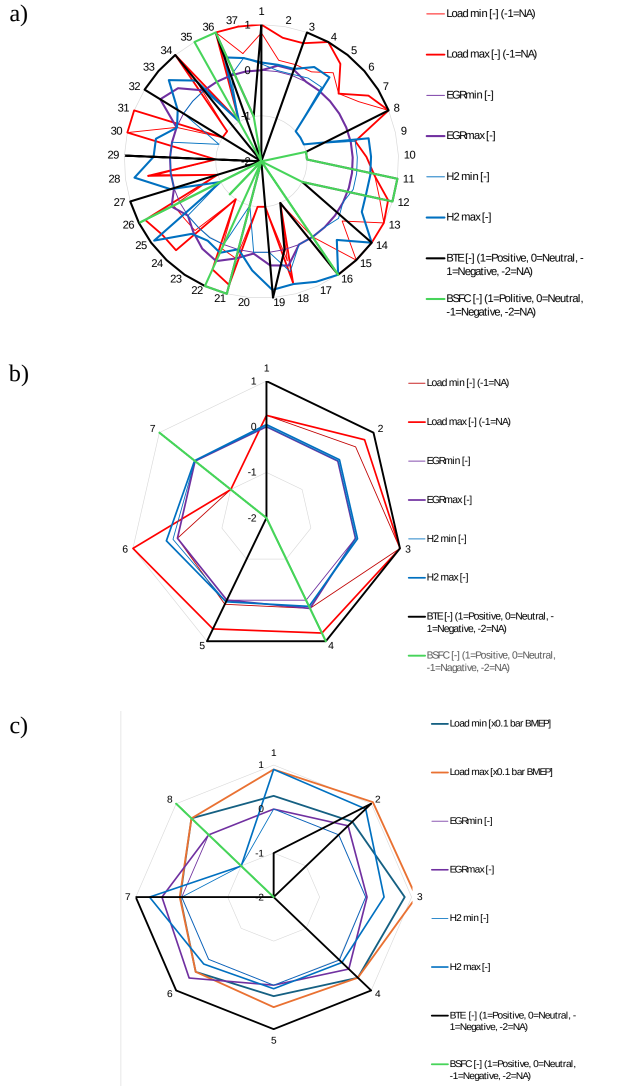

Fig. 2. The effect of load, EGR and H2 supply on BTE and BSFC for DF ICEs ignited by diesel fuel; a) for ICE load [%], EGR [%], and H_2 supply [%], b) for ICE load [%], EGR [%], and H_2 supply [lpm] approximately converted to [%], c) for ICE load [×0.1 bar BMEP], EGR [%], and H_2 supply [%], based on data from [38]. There are shown minimal and maximal limits for load (Load min and Load max, respectively), EGR (EGRmin and EGRmax, respectively) and H_2 supply (H_2 min and H_2 max, respectively) in the Figure

that can enhance the BTE of diesel ICEs is the high energy content of H_2. This effect arises from H_2's elevated calorific value, which drives the H_2-diesel combustion process toward completion, resulting in better ICE efficiency [47, 112]. Although higher calorific fuels generate more heat during combustion, this does not necessarily ensure complete combustion.

The completeness of the combustion process depends on the A/F ratio and the mixing of fuel and air within the combustion chamber. Moreover, incorporating H_2 into diesel fuel can improve A/F mixture homogeneity due to its gaseous state [23, 47], resulting in rapid energy release and enhanced combustion [79].

Incorporating H_2 into diesel fuel can enhance diesel ICE BTE through various mechanisms. One approach is to achieve a leaner equivalence ratio and reduce combustion duration [55]. However, the effect of H_2 addition on the equivalence ratio may vary depending on specific ICE operating conditions and the amount of H_2 introduced. Although injecting H_2 via the inlet port may slightly reduce airflow, leading to a leaner mixture equivalence ratio, increasing H_2 percentage can also result in a richer mixture. Nevertheless, with increased H_2 addition rates, the overall A/F ratio can be maintained at or near stoichiometric to avoid efficiency reduction caused by higher H_2 levels. Also, the heat capacity ratio (adiabatic index) of H_2 exceeds that of hydrocarbon fuels, potentially enhancing diesel ICE BTE. Additionally, the rapid combustion rate of H_2 may reduce heat loss to the surroundings, further improving BTE [108]. However, increasing H_2 beyond a certain threshold may cause knocking [80]. The short quenching distance of the H_2 flame increases the likelihood of flame contact with combustion chamber walls, resulting in increased convective heat transfer and reduced BTE at high H_2 content [112]. Therefore, the precise influence of H_2 addition on BTE depends on specific ICE configuration and operating conditions.

While some studies indicate that H_2 addition to diesel fuel improves combustion efficiency, others suggest the opposite [28, 87], Varde and Frame [100] proposed that incorrect piston positioning relative to peak in-cylinder pressure due to H_2-diesel mixing may reduce diesel ICE BTE. This issue may be resolved by adjusting diesel fuel injection timing, either advancing or retarding it, to optimize combustion timing and mitigate negative impacts on ICE performance. Although H_2 addition into the intake air increases heat absorption by H_2 molecules, it does not necessarily reduce flame temperature. H_2 addition may lower oxygen availability for combustion, potentially reducing combustion efficiency [67]. It is essential to note that H_2 has a higher molar heat capacity than nitrogen, which can increase the overall heat capacity of the mixture. Nonetheless, H_2 addition often leads to an increased overall equivalence ratio, raising combustion temperature. Conversely, low BTE in H_2-diesel dual-fuel operation can be attributed to heat losses resulting from the short flame quenching distance and the high thermal conductivity of H_2, which increases convective heat losses and reduces overall efficiency [26]. Heat loss rates also rise when H_2 is mixed with diesel due to increased wall heat flux, lowering BTE [65].

H_2 addition to diesel under varying ICE loads may result in differing efficiency trends [21, 102].

H_2 addition can reduce BTE under low loads because diesel injection rates decrease, possibly resulting in insufficient pilot fuel to fully combust added H_2. At higher ICE loads, BTE improvements are observed due to increased pilot diesel injection, providing adequate ignition energy for gaseous fuel combustion [57]. H_2 may enhance diesel combustion at higher loads due to the broader flammability limits of its premixed flames, resulting in improved A/F mixture combustion. Additionally, increasing H_2 supplementation at higher loads can increase in-cylinder pressure thanks to its rapid combustion and wide flammability limits [25]. These factors, when combined, can improve BTE in H_2-diesel dual-fuel operation at high loads. In dual-fuel ICEs, H_2 and diesel fuel are injected separately.

The H_2 inclusion rate is typically independent of ICE load and speed, regardless of the injection method, allowing the adjustment of the H_2-to-diesel ratio to ensure consistent combustion and improved efficiency.

The comparative BSFC metric represents fuel consumption per unit brake power (BP) output [109]. Two approaches determine BSFC in diesel ICEs running on H_2 fuel. The first divides the combined mass flow rates of H_2 and diesel by generated power [21, 45, 66]. The second converts the H_2 mass flow into an equivalent diesel amount based on lower heating values, then sums the diesel and converted H_2 mass flows before dividing by the power output [42, 43]. Both express BSFC in g/kWh or kg/kWh. The second method is considered more practical and reliable, as the first may be misleading for fuels with different densities and energy contents [75].

Many studies [14, 46] demonstrated that H_2 addition to intake air reduces BSFC due to its high diffusivity and flame speed, facilitating uniform mixing and improved combustion, increasing BP while reducing BSFC [23, 45,–47, 90]. However, excessive H_2 introduction may increase BSFC due to oxygen limitation, causing incomplete combustion [45].

Although some studies show H_2 improves diesel ICE efficiency, others dispute this [42, 87], This can occur because H_2 addition reduces available oxygen in the combustion chamber, impairing combustion [45]. Mismatches between diesel injection timing and H_2 addition can cause suboptimal combustion timing and insufficient combustion duration, lowering BP and raising BSFC. Brake Specific Energy Consumption (BSEC) is a more reliable efficiency metric, as it is unaffected by fuel characteristics [33]. H_2 addition may improve BSEC by accelerating combustion reactions and enhancing mixture homogeneity [20, 23, 46, 95]. However, excessive H_2 can reduce local oxidant concentration and combustion efficiency [29]. Some studies report BSEC increase due to the mismatch between diesel ICE combustion and gaseous H_2 [48], and increased H_2 mass flow may exacerbate this [108].

The elevated flame temperature of H_2 can increase peak in-cylinder pressure and heat release rates in diesel ICEs. H_2 addition can shorten combustion duration owing to rapid flame speed and faster A/F mixing. However, H_2 inclusion may lengthen ignition delay due to low cetane number and higher auto-ignition temperature. Due to its carbon-free nature and enhanced mixture uniformity, H_2 can significantly reduce emissions of CO, CO_2, HC, PM, smoke, and soot. Nonetheless, H_2 may increase NO_x emissions due to higher in-cylinder peak pressure and temperature [38].

The effect of load, EGR, and H_2 supply on particulate matter (PM), hydrocarbons (HC), NO_x, CO, and CO_2 emissions for DF ICEs excited by diesel fuel is shown in Figure 3. For data in Fig. 3a, 10.1%, 5.4%, 2.7%, 1.1%, and 30% of analyzed cases exhibited missing data for PM, HC, NO_x, CO, and CO_2 emissions, respectively; 8.1%, 21.6%, 43.2%, 8.1%, and 2.7%, respectively, showed reductions; 2.7%, 1.1%, 8.1%, none, and none, respectively, showed no effect; and 78.3%, 62.1%, 45.9%, 81%, and 67.5%, respectively, showed increases. For Fig. 3b, 14.2% of cases had missing data for PM, HC, NO_x, CO, and 28.5% for CO_2 emissions; 14.2% showed reductions for PM, HC, NO_x, and

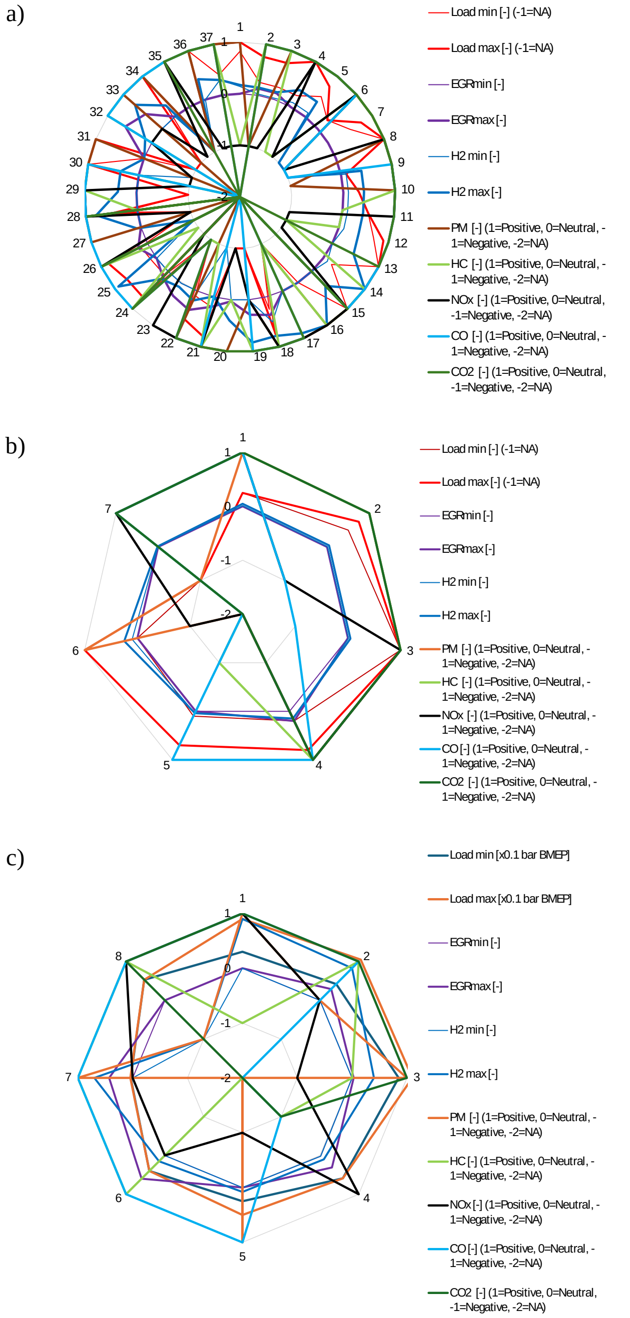

Fig. 3. The effect of load, EGR and H_2 supply on PM, HC, NO_x, CO and CO_2 emissions for DF ICEs ignited by diesel fuel; a) for ICE load [%], EGR [%], and H_2 supply [%], b) for ICE load [%], EGR [%], and H_2 supply [lpm] converted approximately to [%], c) for ICE load [×0.1 bar BMEP], EGR [%], and H_2 supply [%], based on data from [38]. There are shown minimal and maximal limits for load (Load min and Load max, respectively), EGR (EGRmin and EGRmax, respectively) and H_2 supply (H_2 min and H_2 max, respectively) in Figure

CO, none for CO_2; none showed no effects; and 71.4%, 71.4%, 57.1%, 57.1%, and 71.4% showed increases. For Figure 3c, 25%, 12.5%, none, 12.5%, and 37.5% had missing data for PM, HC, NO_x, CO, and CO_2; 12.5%, 25%, 25%, 12.5%, and 12.5% showed reductions; 12.5%, 12.5%, 37.5%, none, and none showed no effect; and 50%, 50%, 37.5%, 75%, and 50% showed increases.

The amount of soot released from the diesel ICE depends on the equilibrium between soot production and its oxidation [105]. H_2 addition to diesel fuel may reduce soot emissions [1, 5]. H_2 can effectively unify the A/F mixture, enhancing combustion efficiency and reducing soot emissions [46]. Incorporating H_2 into diesel fuel may lower carbon levels or increase the H/C ratio of the fuel, thereby reducing soot emissions [61]. By decreasing the proportion of diesel fuel in the mixture, soot oxidation may be enhanced while initial soot formation is reduced [94]. Smoke is an apparent byproduct of incomplete combustion. H_2 addition to diesel fuel may reduce smoke emissions due to the carbon-free nature of gaseous H_2 or an increased H/C ratio in the A/F mixture [81, 83]. The combustion of H_2 generates water and does not produce smoke emissions [80]. The high diffusivity of H_2 may improve A/F mixture uniformity and increase O_2 availability, further reducing smoke emissions [66]. The intense flame produced during H_2 combustion can oxidize carbon particles arising from diesel combustion [82]. The formation of a premixed H_2-air charge during DF operation may eliminate the source of smoke emissions from diesel ICEs [101]. However, excessive H_2 induction may increase smoke emissions by creating an overly rich A/F mixture [78].

PM consists of carbon-based substances resulting from the incomplete combustion of hydrocarbon fuels [80]. PM is a complex pollutant that includes both soluble and insoluble fractions, as well as dry components [98, 106]. Soot, classified as an insoluble fraction, constitutes a significant portion of PM (slightly over 50%) [98]. The remainder of PM (~50%) comprises unburned hydrocarbons (UHCs), partially oxidized hydrocarbons, unburned or partially burned lubricating oil, wear particles, and sulfates (SO_4^{2-}) derived from the fuel [60, 98]. The majority of soot consists of elemental carbon, which adsorbs organic compounds such as polycyclic aromatic hydrocarbons and their derivatives, sulfates, nitrates (NO_3^-), metals, and various trace elements [13]. PM particles exist in both liquid and agglomerated solid forms. Primary particles in the liquid phase are typically volatile organic compounds and sulfates, ranging in size from 5 to 50 nm. Agglomerated particles mainly consist of soot, volatile and nonvolatile organic fractions, metallic residues, and sulfates, with sizes ranging from 50 to 500 nm [36]. Soot aggregates primarily from inside the combustion chamber, while PM is generated outside it [36]. PM may decrease with H_2 enrichment due to the absence of carbon in H_2 and a reduced diesel fuel injection rate [57]. Adding H_2 to diesel fuel may increase flame temperature and improve hydrocarbon combustion, reducing PM generation [67]. Replacing diesel fuel with H_2 can create a more uniform A/F mixture, reducing fuel-rich zones and lowering PM emissions. Incomplete combustion in fuel-rich zones near injector sprays can result in PM formation [58]. Adding H_2 may decrease both particle size and concentration due to its inhibitory effect on hydrogen abstraction and acetylene (C_2H_2) addition processes [114].

Furthermore, it appears that the agglomeration of additional particles into larger clusters can be reduced by incorporating H_2 into ultra-low-sulfur diesel [115]. H_2 addition may also alter the nanostructure of primary particles emitted from the diesel ICE. A shift from a "turbostratic interlayer" to an "onion-like" structure was observed with H_2

addition at 1200 and 1800 rpm under 30% load. Moreover, the "shell-core" structure can transition to a “shell-amorphous” structure with H_2 addition at 1200 and 1800 rpm under 70% load. Compression ignition (CI) diesel ICEs generate PM mainly due to non-uniform combustion resulting from localized fuel-rich zones within the combustion chamber [15]. H_2 can promote a more uniform A/F mixture, reducing PM emissions. H_2 addition may also lower PM emissions from ICEs running on biodiesel (BD) due to a reduced proportion of carbon-containing BD in the A/F mixture [12, 63, 113]. The product of H_2 combustion is water, not PM [15]. The main factors influencing PM oxidation in CI ICEs are the O_2 concentration and temperature inside the cylinder.

UHC compounds are typically found in low-temperature regions of the combustion chamber, such as near cylinder walls, where the temperature is insufficient for complete combustion of the A/F mixture [22]. Incorporating H_2 may reduce UHC emissions from diesel ICEs due to the absence of carbon in H_2 fuel [10]. Introducing H_2 into the intake air may extend the ignition delay, allowing for better A/F mixing prior to ignition [58]. Gaseous H_2 can fully homogenize the A/F mixture due to its high diffusivity [46], improving combustion efficiency and reducing UHC emissions. The wide flammability range and short quenching distance of H_2 may also improve the combustion of A/F mixtures [108]. The rapid burning rate of H_2 can enhance diesel combustion, leading to lower UHC emissions [82]. H_2 addition may increase in-cylinder temperature, enhancing UHC oxidation after combustion [47].

However, H_2 incorporation into diesel fuel may also increase UHC emissions [20, 42]. This may occur if the pilot fuel supply is insufficient to fully ignite the gaseous fuel [26], or if H_2 reduces the O_2 concentration in the A/F mixture, resulting in incomplete diesel fuel combustion [66]. Rapid H_2 combustion may consume most of the available O_2, leading to incomplete oxidation of diesel injected late in the cycle [100]. The high burning speed of H_2 may also increase UHC emissions due to flame quenching [81]. Extending the ignition delay under fuel-lean conditions with H_2 addition may also result in incomplete combustion [114].

The formation rate of NO_x in diesel ICEs largely depends on O_2 concentration, A/F mixture residence time, and in-cylinder temperature. Atmospheric N_2 and O_2 can undergo various chemical reactions, forming NO_x in high-temperature regions [39]. Conventional diesel combustion produces high levels of NO_x and soot due to diffusive flame characteristics [48]. Low-temperature combustion can reduce both NO_x and soot emissions from diesel ICEs [51], [76]. Various low-temperature combustion strategies, such as homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), and reactivity-controlled compression ignition (RCCI), have been developed and studied [51]. RCCI can operate over a wide load range, achieving near-zero NO_x and soot emissions by adjusting fuel blends and injection strategies [49, 50, 111]. RCCI ICEs control in-cylinder reactivity to manage the combustion phase [51]. In this dual-fuel process, at least two fuels with different reactivities are used [30, 49]. A/F homogeneity is achieved by introducing low-reactivity fuels (e.g., methanol, natural gas, gasoline, ethanol) through the intake port, while ignition is initiated by direct injection of a high-reactivity fuel (e.g., diesel, biodiesel, dimethyl ether) [11, 34].

In RCCI diesel combustion, combustion chamber regions are cooler compared to conventional diesel, significantly reducing heat transfer from the piston bowl and improving BTE [44]. While RCCI offers attractive features, its CO and UHC emissions are typically higher than in standard diesel combustion [34]. When H_2 is added to low-reactivity fuels, RCCI ICEs produce much lower CO and UHC emissions, as shown by Kakoee and Gharehghani [41]. However, H_2 addition beyond a certain threshold may increase NO_x and soot emissions by raising in-cylinder temperature.

H_2 addition to diesel fuel may increase NO_x emissions [20], [107]. The high calorific value of H_2 can elevate peak in-cylinder pressure and temperature, leading to higher NO_x emissions [77]. The rapid flame speed of H_2 can promote complete combustion, further increasing pressure and temperature [85]. H_2 addition may also raise local temperatures earlier in the expansion phase, accelerating NO_x formation [100]. The increased ignition delay due to H_2 addition can create a more homogeneous A/F mixture before ignition, raising in-cylinder temperature and contributing to higher NO_x emissions [58]. NO_x emissions from H_2 port injection can exceed those from H_2 induction [101]. Port injection can improve combustion and volumetric efficiency while increasing combustion temperature [101].

However, H_2 incorporation into diesel fuel may also reduce NO_x emissions if the engine operates with a leaner mixture [83]. A very lean equivalence ratio can lower peak combustion temperature, reducing NO_x emissions [81]. H_2 can promote a more uniform A/F mixture, eliminating fuel-rich zones and allowing temperature to rise more gradually, thus reducing NO_x production [1]. NO_x reduction may also occur at high H_2 supplementation rates if combustion duration increases, lowering the heat release rate [28]. Water vapor (H_2O) generated from H_2 oxidation may lower in-cylinder temperature and further reduce NO_x emissions [108]. H_2 addition may reduce the amount of diesel fuel consumed during the diffusive combustion phase, which is a major source of NO_x [108].

H_2 introduction into the intake air can reduce CO emissions [20, 112] due to a lower C/H ratio in the fuel mixture [32]. The high diffusivity of H_2 promotes a homogeneous combustible mixture, enhancing combustion and reducing CO emissions [42, 77]. The rapid flame speed of H_2 enhances combustion and increases in-cylinder temperature, thereby further reducing CO emissions [66, 77]. This reduction may also be linked to the ability of H_2 to operate at lean equivalence ratios [84], [112]. However, H_2 addition to diesel fuel under certain conditions may increase CO emissions. This can occur if H_2 reduces O_2 availability, leading to incomplete oxidation [26]. Elevated in-cylinder temperature from H_2 addition may promote CO_2 dissociation into CO and O [56]. The rapid H_2 reaction rate may deplete O_2 in the combustion chamber, leaving less for CO oxidation. O_2 may be consumed in H_2 oxidation and radical formation [10]. H_2O from H_2 oxidation may also participate in the steam reforming of diesel hydrocarbons, increasing CO emissions [10]. H_2 addition may increase CO production under high engine loads due to reduced O_2 and shorter reaction times [82]. However, CO emissions may decrease when H_2 is blended with diesel under low loads, due to ample O_2 in leaner A/F mixtures [82].

H_2 incorporation into diesel fuel may lower CO_2 emissions [52, 112], due to the carbon-free nature of H_2 [66]. Furthermore, increasing the overall H/C ratio of the fuel blend by adding H_2 can shorten combustion duration and improve combustion efficiency [61, 77]. The high diffusivity of H_2 may also create a more uniform premixed combustible mixture [20], driving combustion toward completion [77]. The rapid flame speed of H_2 can improve fuel blend combustion efficiency, potentially reducing CO_2 emissions [20]. However, under high engine loads, H_2 addition may reduce CO_2 emissions due to combustion instability and O_2 deficiency [80].

Sutkowski and Mareczek [93] examined the MUZG and WUZG systems designed for managing the combustion of H_2-based fuels. These systems enable operation even with pure H_2 while effectively controlling combustion parameters, such as preventing knock, regulating combustion temperature, and controlling flame speed, among others. This is achieved by early detection of knock or misfire signals, monitoring exhaust temperature, and implementing corrective actions in the next engine cycle if deviations are detected. The WUZG system also enables independent monitoring of each cylinder with its individual mixture composition, or temporary deactivation of a cylinder if combustion becomes unstable, thereby potentially preventing cylinder failure. The system logs engine operation and can detect even minor deviations from target performance, enabling preventive measures to be taken before damage occurs. This prevents scenarios where engine power is limited or the engine must be shut down due to operational faults. The integrated MUZG/WUZG system offers enhanced operational flexibility, allowing transitions between different fuel supply systems. MUZG is prioritized for fuels with low pressure and low H_2 content, while WUZG is preferred for higher-pressure or higher-H_2 fuels. The system can be expanded to accommodate additional hydrocarbon gases blended with H_2. MUZG is applicable to bi-fuel engines operating on both liquid and gaseous fuels (e.g., biodiesel and biomethane), whereas WUZG can be used in dual-fuel engines that combine biodiesel with H_2 or alcohols.

Longwic et al. [54] examined the acceleration of a diesel ICE fueled by both diesel and H_2 on a test bench equipped with a 1.3 Multijet diesel, H_2 storage, and measurement instruments (Table 1). Empirical tests included ICE assessment at idle and at specific speeds using a chassis dynamometer, as well as vehicle acceleration in selected gears from predefined engine speeds. They found that supplying both diesel and H_2 to the intake manifold increased the mean indicated pressure at idle by approximately 144% compared to diesel-only operation. The amount of heat release, peak combustion pressure, and maximum rate of pressure rise also increased. However, for engine operating conditions other than idle, there was a decrease in heat output, heat release rate, combustion chamber pressure, and mean indicated pressure. In these tests, the H_2 flow was controlled to ensure no gas accumulation and prevent possible explosions in the intake manifold under any operating condition. Stock diesel fuel injection timing maps were not modified. Currently, it appears that H_2 supplied to the intake manifold can improve engine performance at idle. However, to achieve safe and noticeable improvements under other conditions, both the H_2 amount and diesel fuel quantity must be adjusted according to the engine's operating parameters.

Longwic et al. [53] tested a diesel engine powered by various fuels using a specialized H_2 injection system with dedicated control software. Control parameters included H_2 injection pressures of 1.5, 1.8, and 2.0 MPa and injector opening durations of 2.5, 3.0, and 3.5 ms.

Analysis of the engine operating in diesel-H_2 dual-fuel mode demonstrates that rapidly changing in-cylinder combustion parameters can be effectively monitored. As H_2 injection duration and pressure increase, the amount of air required for proper combustion also rises. The control system responded by reducing the amount of diesel fuel injected per cycle as additional H_2 was provided. However, the range of H_2 pressure and injection duration was limited, so the reduction in diesel fuel quantity was nearly the same across the tested range. Proper regulation of the diesel-H_2 ratio is essential for stable engine operation under load.

Research on a diesel engine operated with H_2 enabled the identification of control parameters for integrating renewable fuel to reduce fossil fuel consumption, specifically diesel. Operating the test vehicle on a dynamometer in 4th gear at 2600 rpm, optimal fast-variable cylinder parameters were achieved with an injector activation time of 3.5 ms at 0.20 MPa. Modified control strategies resulted in an average 21.5% reduction in diesel consumption.

Noga and Moskal [64] examined the suitability of a pressure-sensing glow plug (PSG) for monitoring combustion in an H_2-powered engine (Table 1). The combustion characteristics of H_2 in spark-ignition (SI) engines differ significantly from those of conventional fuels, making cylinder pressure monitoring essential for optimizing power, efficiency, and minimizing NO_x emissions, which are the primary pollutants in H_2 engines. A PSG was selected for its cost-effectiveness, availability, and durability. Initial tests were conducted on a small single-cylinder SI engine coupled to a 48 V generator. Tests were run at various speeds and generator loads using gasoline with a research octane number (RON) of 95. To simulate H_2 combustion and achieve faster pressure rise, tests were also performed with unaltered light gasoline (lower RON). Comparing the PSG signal with that of a reference pressure transducer installed in the cylinder allowed characterization of PSG behavior under different conditions. Pressure waveforms from both sensors varied according to engine speed and load. The developed transfer functions from the PSG signal to actual in-cylinder pressure may be applied to other engines, allowing cost-effective combustion monitoring in H_2 SI engines after appropriate calibration.

Cupiał and Szwaja [18] studied producer gas combustion in SI and DF CI engines using a diesel pilot (15% of nominal amount), with compression ratios (CR) of 8, 12 (SI engine), and 17 (CI engine) (Table 1). The study focused on combustion instabilities, including cycle-to-cycle variability and knock phenomena. H_2 combustion was also investigated for comparison. The authors found that producer gas is knock-resistant, even with 16% H_2 content. However, significant cycle-to-cycle variability was observed when producer gas was burned in the SI engine. The DF CI engine could operate more efficiently and stably with producer gas, with no misfires or knock. On the other hand, H_2 combustion in the DF engine resulted in heavy knock, making it unsuitable as a primary fuel. Conversely, gases with high H_2 content are generally not prone to knock, especially when CO_2 is present in quantities similar to H_2, as this greatly increases resistance to knocking.

Tira et al. [97] examined the performance of diesel ICEs fueled with biogas (BG) and H_2 (Table 1). In these experiments, simulated BG (60% CH_4 and 40% CO_2 by volume) and H_2 (2% by volume) were introduced into the intake manifold, while diesel fuel was injected into the cylinder as a pilot ignition source. The results showed that BG and H_2 reduced PM levels compared to pure diesel combustion. Specifically, total PM decreased by up to 39% and smoke by 33%. A slight increase in particle count was observed, with particle size distribution shifting toward the nucleation mode, which is advantageous for after-treatment systems. However, BTE decreased with the addition of gaseous fuel.

Siadkowska and Barański [89] investigated (direct H_2 injection) in a four-cylinder, four-stroke DF ADCR ICE (Table 1). Analyzed parameters included mean effective pressure, peak pressure, crank angle at peak pressure, and heat release. Both early and late direct H_2 injection timing strategies were tested. The authors found that:

– Significant statistical differences were observed in burning process parameters between early and late injection, based on the Student's t-test ($\alpha = 0.05$): for IMEP (56%), peak pressure (88%), heat released (56%), and crank angle at peak pressure (56%)
– In 94% of measurement points, the coefficient of variation for IMEP remained below 5%, indicating stable combustion progression
– Changing direct H_2 injection timing from early to late affects only the combustion process; the degree of this influence depends on H_2 dosage and initial torque. At the highest H_2 dosages, the maximum load threshold of the test setup was nearly reached, resulting in engine knocking, which may account for the observed instabilities.

Depczyński et al. [24] examined the effects of H_2 as an additive to gasoline in ICEs within a hybrid powertrain, focusing on efficiency and environmental sustainability (Table 1). Their study centered on evaluating fuel consumption and CO_2 emissions during the NEDC driving cycle. A mathematical model was developed incorporating H_2 addition and hybrid powertrain operation during the NEDC cycle. They found that a 2% increase in H_2 content in gasoline reduced BSFC by 2.8–3.5%, depending on engine speed. The hybrid system enabled effective energy recovery during braking, enhancing overall system efficiency.

Shadidi et al. [86] investigated the effects of using H_2 as an auxiliary fuel in both SI and CI ICEs on engine efficiency and emissions. Utilizing H_2 as a fuel reduces torque, power, and brake thermal efficiency (BTE), while simultaneously increasing brake specific fuel consumption (BSFC). H_2 use significantly lowers CO, UHC, CO_2, and soot emissions; however, NO_x emissions increase.

Stępień [92] reviewed the unique physical, chemical, and operational properties of H_2 used as an ICE fuel, focusing on H_2 port fuel injection (PFI) and direct injection (DI) technologies. The author compared various fuel injection and ignition strategies, highlighting the benefits of combining selected solutions. Potential risks of improper H_2 combustion – such as pre-ignition, delayed ignition, knocking, and backfiring – were analyzed. Special attention was given to optimizing the air-fuel ratio for combustion quality, NO_x emissions, and engine efficiency, as well as exhaust gas treatment. Required modifications to adapt conventional ICEs for H_2 operation were also discussed. It was found that H_2 represents a promising alternative fuel for SI ICEs, significantly improving efficiency and reducing emissions to a fraction of the levels of conventional fuels. However, its use has notable drawbacks, including elevated NO_x emissions, reduced durability, and reliability concerns.

Fabiś et al. [29] studied the relationship between combustion noise and operational parameters of an ICE powered by LPG, CNG, and CNG-H_2 mixtures in comparison to a gasoline-fueled ICE. Indicators of various resonances within the combustion chamber and related vibration signals from the engine's cylinder block were examined for a single combustion cycle. A four-cylinder, 1.6 dm^3 SI ICE modified to operate on LPG, CNG, and CNG-H_2 mixtures with H_2 volumetric fractions of 5, 10, 15, 20% to 30% was evaluated. For comparison, gasoline was used as the reference fuel. The authors found that fluctuations in in-cylinder pressure significantly affect the vibration signal from the engine block. For CNG-H_2 mixtures of 20% and 30% H_2, a distinct reduction in combustion noise was observed compared to the other fuels studied.

Sharma and Dhar [88] investigated how different compression ratios (CRs) influence the maximum possible H_2 energy share in a DF ICE. A numerical model was used to examine combustion and emission characteristics with H_2 introduced via port fuel injection (PFI). They found a trade-off between maximum H_2 energy share and CR. The knock-limited maximum H_2 energy share increased from 20% to 45% as the CR was reduced from 19.5 to 14.5. With increasing H_2 energy share, emissions – except for NO_x – typically decreased across all tested CRs.

Jamrozik et al. [40] reported that investigating DF combustion with diesel and H_2 (0–30%) showed that adding up to 30% H_2 increased peak combustion pressure by 13%, increased heat release rate by 46%, and raised the maximum rate of pressure rise by 35% under full load conditions. Although efficiency improved with H_2 concentrations up to 25%, engine stability decreased at higher H_2 levels, and NO_x and HC emissions increased. Therefore, careful optimization of H_2-diesel mixtures is essential to enhance efficiency while managing emissions [91].

Pham et al. [69] examined the efficiency, combustion, and emission characteristics of ICEs using alternative fuels (H_2, NG, BD) in DF CI ICEs. Due to differing fuel properties, DF operation typically improved brake specific energy consumption (BSEC) compared to standard diesel operation.

Table 1. The characteristics of selected dual-fuel internal combustion engines powered by H_2

Refs	Model ICE type	Combustion system	H_2 supply method	Bore × stroke [mm]	Displacement [dm^3]	CR [-]	Max power [kW]/ Speed [rpm]	Max torque [Nm]/ speed [rpm]
[54]	Fiat Qubo 1.3 MultiJet 4-cylinders, vertical 4-stroke forced air cooled diesel	Multipoint injection system	H_2 is supplied from the cylinder to the inlet channel via tubing. Pressure controlled by a valve and measured with a manometer. Flow rate measured by a Vogtlin mass flow meter in the line supplying H_2 to the system	69.6 × 82	1.248	16.8:1	55/4000	190/1500
[18]	Deutz F2L511 2-cylinders, 4-stroke, air cooled, diesel	6-hole injector for adjustable diesel fuel dosing. One cylinder modified to operate in SI mode	H_2 or producer gas supplied via ~~an~~ injection system mounted on the inlet manifold or via a mixer	100 × 105	1.650 (unmodified), 0.825 (modified)	8:1; 12:1 (1 cylinder modified to operate at SI mode); 17:1 (diesel)		
[97]	Lister-Petter TR1 1-cylinder, Bowl-in-piston, air cooled diesel	3-hole direct injection. Pilot liquid fuel injected near the end of the compression phase	Bottled H_2 supplied via the intake manifold (~2% of air intake). H_2 premixed before entering the combustion chamber	98.4 × 101.6	0.773	15.45:1	8.6/2500	39.2/1800
[89]	Andoria-Mot ADCR ICE 4-cylinder, 4-stroke DF diesel ICE		The glow plugs replaced by injectors for ~~of~~ compressed H_2		2.636	17.5:1		
[64]	WEIMA 168FA 4-stroke, SI, 1-cylinder, air cooled		Unmodified light gasoline as a solvent to simulate H_2 supply		0.163		3.8/3600	
[24]	VAZ-21081 ICE, 4-stroke, 4-cylinder, gasoline	distributed FI system	H_2 supplied as a part of hybrid system	76 × 60.6	1.1	9:1	39.7/5600	77.9/3600
[8]	1-cylinder, air-cooled, (DI), 4-stroke HATZ D-series DI diesel ICE		H_2 fed into the mixer in the intake manifold. Diesel fuel flow rate controlled by a modified original diesel FI system					

However, the overall efficiency of DF ICEs – measured by BTE and volumetric efficiency – remained considerably lower. DF operation significantly increased in-cylinder pressure and heat release rate while prolonging the ignition delay. Emission characteristics revealed a trade-off between NO_x and HC emissions: NO_x, PM, and smoke decreased, depending on engine load, blend ratio, and injection timing. However, HC and CO emissions in DF ICEs were several times higher than in conventional diesel engines.

Tutak et al. [99] studied a DF ICE running on diesel and NG, with H_2 enrichment to improve the NG component. They found that increasing H_2 levels improved combustion efficiency, reducing combustion duration by 30% and halving the time to 50% mass fraction burned. The maximum H_2 energy share was determined to be 19%; beyond this, engine stability declined due to increased cycle-to-cycle variability and knocking.

Rorimpandey et al. [73] emphasized the role of injection sequence, timing, and ambient temperature on combustion. Injecting the pilot diesel before H_2 cooled and delayed H_2 ignition. In contrast, injecting H_2 first improved air–gas mixing, but lean combustion occurred if H_2 was injected later, especially at low ambient temperatures.

Bakar et al. [8] explored the effects of varying H_2 flow rates on combustion, efficiency, and emissions in a DF diesel ICE. Tests conducted at various engine speeds and H_2 flow rates revealed that specific flow rates had a significant impact on engine efficiency and emissions. In particular, BTE increased at lower flow rates due to shorter combustion duration and improved phasing, while higher flow rates increased CO, CO_2, and smoke emissions.

Numerous studies indicate that increasing the H_2 proportion in DF ICEs improves combustion efficiency and reduces emissions, but requires careful management to prevent engine instability and increased NO_x emissions.

These studies highlight the influence of CR, injection timing, and H_2 flow rate on efficiency, demonstrating that while H_2 enhances fuel efficiency and reduces emissions, careful integration is essential to ensure engine stability and prevent combustion-related issues.

Wagemakers and Leermakers [103] reported that using H_2 or SG in DF combustion generally increases NO_x emissions, likely due to higher fire temperatures and burning speeds. HC and CO emissions also tend to increase in DF combustion, primarily due to incomplete combustion of mixtures trapped in crevices. Efficiencies of various gaseous fuels are similar, with minor gains observed for H_2 and LPG, and slight reductions for NG and SG.

Hosseini et al. [38] explained that although SG is low in carbon, its use in diesel ICEs may reduce thermal efficiency and increase BSFC, mainly due to the low volumetric calorific value and high CO_2 content of SG. Nanoparticles and oxygenated additives may help compensate for this by promoting complete combustion, though further research is needed. Adding less energetic SG reduces peak heat release rate and in-cylinder pressure in diesel ICEs. The high specific heat capacity and CO_2 content of SG may also extend ignition delay. Reduced burning rates and adiabatic flame temperature may result in longer combustion duration.

Adding SG to diesel/BD fuel may increase CO, CO_2, and UHC emissions from diesel ICEs. CO in SG and high charge dilution can lead to incomplete combustion. Oxygenated additives to diesel/BD may raise CO_2 emissions due to enhanced oxidation. These additives may also increase UHC emissions, as higher heat of vaporization can lower in-cylinder temperature. Adding nanoparticles to diesel/BD could reduce UHC emissions by promoting oxidation, but further research is required [38].

Integrating SG into diesel/BD fuel may reduce NO_x emissions from diesel ICEs. SG may lower concentrations of N_2 and O_2 in the intake air, decreasing the likelihood of thermal NO_x formation. SG may reduce PM emissions by decreasing the liquid fuel injection rate, which is more prone to sooting. However, adding SG may also increase soot/smoke emissions by lowering in-cylinder O_2 concentration and causing incomplete combustion. Conversely, some studies suggest that SG can lead to more homogeneous fuel mixtures and lower local air-fuel equivalence ratios, thus reducing soot/smoke emissions [38].

Ando et al. [6] evaluated the performance of low-heating-value gases from gasification and two-stage pyrolysis/reforming in a naturally aspirated single-cylinder SI ICE with CRs of 9.4 and 11.9. The gas from gasification was rich in H_2 (lower heating value of 3.83 MJ/Nm³), while the two-stage pyrolysis gas was rich in CH_4 (lower heating value of 4.2 MJ/Nm³). A gas mixer replaced the carburetor to control the air–fuel ratio. Both fuels achieved similar BTE to CNG. The H_2-rich gas enabled stable engine operation at λ up to 2.00. Compared to both CNG and CH_4-rich pyrolysis gas, NO_x and HC emissions were significantly lower for the H_2-rich gas. The CH_4-rich gas also exhibited very low NO_x levels.

Chintala and Subramanian [16] reported that PM emissions can be notably reduced while improving thermal efficiency by using H_2 in DF ICEs (diesel-H_2). In H_2 DF ICEs, HC, CO, and smoke emissions approach zero, while CO_2 and CH_4 emissions from CI ICEs are substantially reduced. However, the maximum H_2 energy share in DF ICEs at rated load is limited to 6–25% due to elevated peak cylinder pressures and pressure rise rates, which can cause knocking and autoignition of the H_2-air mixture. In addition, NO_x emissions in DF mode are 29–58% higher than in conventional diesel mode due to high localized in-cylinder temperatures. Appropriate optimization strategies can increase the maximum H_2 energy share to 79% while reducing NO_x emissions to levels comparable to those of conventional diesel operation.

Mehra et al. [59] observed that incorporating H_2 into CNG (HCNG) ICEs enhances BTE and significantly reduces cycle-to-cycle variations (CCV) and BSFC due to H_2's combustion characteristics. HCNG is safer than pure H_2 due to its lower energy content. Under certain conditions, the thermal efficiency of HCNG ICEs is notably higher than that of CNG ICEs, without increasing harmful emissions. However, adding H_2 to natural gas increases NO_x emissions due to higher combustion temperatures. This can be mitigated by lean combustion or three-way catalyst (TWC) systems. Using EGR with TWC reduces combustion temperature, directly lowering NO_x emissions. THC, CO, CO_2, and CH_4 emissions decrease notably with H_2 addition. However, H_2 also increases the engine's tendency to knock due to peak cylinder temperatures and high ignitability. H_2 enables higher CRs without combustion instability compared to CNG, further enhancing BTE. For SI ICEs, optimal performance is achieved with 20–30% H_2 enrichment. HCNG ICEs offer better fuel efficiency than conventional CNG ICEs, and direct fuel injection (DFI) systems further reduce BSFC compared to PFI.

According to [110], blending H_2 with natural gas in SI ICEs shifts the lean limit toward a leaner mixture, increasing combustion speed and temperature. Even a small addition of H_2 by volume catalytically improves hydrocarbon ignition, and in pure CNG, the required spark advance can be reduced due to H_2's high flame speed. HCNG mixtures improve engine efficiency, especially at low loads, but with increasing H_2 content from 10% to 30%, NO_x emissions rise by 4–20% due to higher in-cylinder temperatures. Implementing about 10% EGR for HCNG blends can significantly reduce NO_x emissions and BSFC compared to natural gas. Maximum brake torque can be achieved under leaner combustion conditions by increasing H_2 content.

Hosseini et al. [38] explained that H_2 can address issues associated with using gaseous fuels (e.g., biogas, methane, CNG, NG, LPG) in diesel ICEs, including extended ignition delay, reduced engine efficiency, slower burning rates, and increased CO and UHC emissions. H_2 can improve efficiency metrics of diesel ICEs running on biogas by offsetting the low calorific value of CO_2-rich biogas and optimizing its combustion. Similarly, increasing H_2 levels can enhance efficiency in diesel ICEs running on CH_4 by accelerating combustion. Notably, CH_4 can compensate for some limitations of H_2 combustion (e.g., short quenching distance). H_2 can offset the low flame speed of CNG and NG, enhancing their combustion in diesel ICEs. H_2 can improve the BTE of LPG-fueled diesel ICEs by stabilizing the LPG flame in lean mixtures. H_2 enrichment can raise the heat release rate and in-cylinder pressure in ICEs with biogas, methane, CNG, and NG by increasing mixture calorific value and laminar flame speed. Adding H_2 may extend the combustion duration of diesel ICEs powered by natural gas and methane by widening flammability limits. Enriching CNG and LPG with H_2 shortens combustion duration by accelerating the burning rate.

Significantly, methane (CH_4) can mitigate certain limitations of hydrogen (H_2) combustion, such as its minimal quenching distance. H_2 can effectively offset the low flame speed of compressed natural gas (CNG) and natural gas (NG), thereby enhancing their combustion in diesel internal combustion engines (ICEs). H_2 has the potential to improve the brake thermal efficiency (BTE) of diesel ICEs fueled by liquefied petroleum gas (LPG) by stabilizing the LPG flame in lean gaseous air-fuel (A/F) mixtures. H_2 enrichment can increase the heat release rate and in-cylinder pressure of diesel ICEs fueled by biogas (BG), methane, CNG, and NG by raising the calorific value and laminar flame speed of the A/F mixture. Adding H_2 may extend the combustion duration of diesel ICEs powered by natural gas and methane by broadening the flammable limits of the A/F mixture. Enriching CNG and LPG with H_2 shortens the combustion duration of diesel ICEs by accelerating the burning rate of the A/F blend [38].

The use of H_2 can reduce combustion duration in diesel ICEs by increasing the burning rate of the A/F mixture [38].

The inclusion of H_2 in BG extends the ignition delay in diesel ICEs due to a decrease in the oxygen content of the intake mixture. Conversely, the addition of H_2 to CH_4, CNG, and LPG may reduce the ignition delay in diesel ICEs due to enhanced combustion kinetics [38].

Emissions of CO and unburned hydrocarbons (UHC) from diesel ICEs can be significantly reduced by enriching BG, CH_4, CNG, NG, and LPG with H_2. This reduction is largely attributed to the partial substitution of carbon-rich fuels with H_2, which accelerates the combustion rate of the gaseous fuel. Incorporating H_2 into BG, CH_4, CNG, and NG may lower CO_2 emissions from diesel ICEs by reducing the carbon-to-hydrogen (C/H) ratio of the gas mixtures. However, H_2 may increase NO_x emissions from ICEs using BG, CH_4, CNG, or NG-diesel blends due to a rise in peak in-cylinder pressure and temperature. Introducing H_2 to LPG may positively reduce NO_x emissions from diesel ICEs by decreasing the extent of high-temperature zones around the diesel flame. Incorporating carbon-free H_2 into BG, CH_4, and CNG can reduce smoke and soot emissions from diesel ICEs. The high diffusivity of H_2 promotes thorough homogenization of the combustible mixture, improving combustion efficiency and reducing smoke emissions [38].

Emerging Indirect Regenerative Evaporative Technology (IRET), also known as the Maisotsenko cycle (M-cycle), may offer complementary benefits for H_2- and diesel-powered combustion engines [116]. When applied to the engine inlet system, this technology can significantly lower inlet air temperature and enhance charge cooling, potentially mitigating knocking, improving power density, and further reducing NO_x emissions [31] – even at high H_2 enrichment rates. The IRET's unique ability for both sensible and latent cooling with minimal water usage is particularly promising for high-efficiency, low-emission engine applications, especially under demanding or transient operating conditions. Recent R&D on Maisotsenko-powered cycles [116] suggests that when integrated with advanced engine management systems, these cooling techniques could enable more aggressive optimization of H_2 supply, EGR rates, and injection strategies, while maintaining combustion stability and minimizing particulate formation. Their adaptability to variable engine loads and ambient conditions makes them a viable candidate for next-generation engine architectures aiming to maximize renewable fuel utilization (e.g., H_2, biodiesel) and minimize environmental impact. Further experimental and numerical research is encouraged to evaluate the real-world performance and durability of such integrated systems, especially in scenarios with high combustion temperatures and aggressive emission control demands.

3. Summary

The present review enabled the current state-of-the-art to be obtained relative to dual-fuel (DF) internal combustion engines (ICEs) supplied with fuel and hydrogen (H_2). The benefits and challenges of using such engines were discussed.

The reviewed ICEs operated within a relatively narrow speed range, 1724 ±528 rpm. The displacement of such ICEs was in a wide range of 1674 ±2325 cm^3. Additionally, ICE minimal loads spanned a wide range of values, from 27.3% ±34%, and similarly, maximum loads reached values in the range of 50–100%. Of course, the ICE load could vary between 0 and 100%. The ICE's CR did not vary too much. The minimum CR reached values varied in the range of 16.41 ±4.72, while the maximum CR values varied in the range of 16.49 ±4.78; thus, variations in CR values are significant.

It should be noted in particular that for many of the analyzed engine cases, there is a lack of data regarding the effect (especially the combined one) of load, EGR, and H_2 supply on BTE and BSFC. For a slightly smaller number of such engine cases, there was a lack of data regarding the effect (especially the combined one) of load, EGR, and H_2 supply on PM, HC, NO_x, CO, and CO_2. Furthermore, comparing data for these engines was difficult because engine load was reported in either percent or bars, and H_2 supply in percent or L/min, necessitating categorization of the data into three different groups. This necessitates the development of a standard for collecting and presenting data from the tested DF ICEs.

For analyzed cases of common effect of varying load, EGR and H_2 supply on BTE and on BSFC, respectively it was found that up to 13.5% of the cases related to their lowering, almost no cases related to no effect on them, as well about 62.5–71.5% and 12.5–58.6% of the cases, respectively, related to their enhancing.

For analyzed cases of common effect of varying load, EGR and H_2 supply on PM, HC, NO_x, CO and CO_2 emissions, respectively it was found that below: 14.2%, 25%, 43.2%, 28.5% and 12.5% of the cases, respectively related to their lowering, while below 12.5%, 12.5%, 37.5%, none and none of the cases, respectively related to no effect on them, and similarly related to their enhancing. Especially positive is the role of EGR in DF ICEs.

The application of H_2 in diesel engines via the dual-fuel (DF) strategy represents a promising pathway to reduce diesel consumption, lower carbonaceous emissions, and decrease dependence on fossil fuels. The review highlights that H_2-DF combustion can significantly reduce CO, CO_2, HC, and PM emissions, while maintaining or improving brake thermal efficiency (BTE) under optimized conditions. However, the technology faces two major technical challenges: elevated NO_x emissions and increased susceptibility to knocking, both of which are strongly influenced by H_2 concentration, engine load, and pilot fuel properties.

To address NO_x emissions, a range of strategies – including exhaust gas recirculation (EGR), selective catalytic reduction (SCR), water injection, urea dosing, external cylinder cooling, and Lean-NO_x traps – have proven effective, with EGR offering a particularly attractive solution due to H_2's tolerance for high dilution rates. Combustion stability and knock resistance can be managed by carefully adjusting the maximum H_2 inclusion rate for each engine configuration and operating scenario, though further research is needed to establish universal guidelines.

The use of H_2 in combination with biodiesel (BD) further reduces reliance on fossil fuels, but the optimal BD/H_2 blend ratio and injection strategy remain to be systematically defined. While H_2 drastically reduces total particulate matter (PM), it may increase the number of ultrafine particles, posing potential health and environmental risks that warrant further investigation.

Incorporating nanomaterials and oxygenated compounds into diesel fuel formulations has the potential to further enhance combustion efficiency and reduce emissions. However, the long-term impacts of these additives on engine durability, emissions, and aftertreatment systems require a comprehensive study. Lifecycle assessments (LCA) are also necessary to evaluate the full environmental benefits and trade-offs of H_2-DF engines, including resource use and end-of-life considerations for advanced materials.

Ultimately, integrating H_2-DF engines with hybrid electric systems may provide additional efficiency gains and enhanced transient performance. Future research should focus on system optimization, health impacts of ultrafine particles, durability of novel materials, evaluation of the viability of advanced evaporative technologies (IRET) [116] and the development of robust, adaptive control strategies for a wide range of applications.

Nomenclature

A/F	air-fuel
BD	biodiesel
BG	biogas
BSFC	brake specific fuel consumption
BP	brake power
BT	brake torque
BTE	brake thermal efficiency
CI	compression ignition
CNG	compressed natural gas
CR	compression ratio
DF	dual fuel
DI	direct injection
EGR	exhaust gas recirculation
FI	fuel injection
ICE	internal combustion engine
LPG	liquefied petroleum gas
PFI	port fuel injection
SG	syngas
SI	spark ignition
UHC	unburned hydrocarbons

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