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An Overview of Hydrogen Applications in Internal Combustion Engines Toward Transport Decarbonization

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Review Article

Abstract

Hydrogen as a fuel exhibits significant potential for integration into energy systems, potentially enabling the decarbonization of the transportation sector and achieving sustainability goals in alignment with global and European Sustainable Development Goals strategies (SDGs). The decarbonization of the energy sector is outlined in the Paris Agreement, which sets specific objectives that United Nations member states are obligated to meet by 2030 and 2050. This paper explores the latest trends in the development and application of hydrogen in internal combustion engines (H_2 - ICE) as a fuel. It covers the fundamental principles of H_2 - ICE operation, including necessary modifications to conventional internal combustion engines (modification of fuel supply systems, combustion chamber design, thermal load management, and H_2 storage systems in vehicles). Additionally, the paper examines the compliance of H_2 - ICE technology with European strategies, including the European Green Deal and Euro 7 emission standards. The European Union's regulatory framework (Hydrogen Strategy and REPowerEU plan) defines guidelines for accelerating the transition to renewable energy sources and achieving energy independence, supported by financial mechanisms that encourage the adoption of hydrogen in the automotive industry. Furthermore, the study provides an analytical overview of industry trends among leading vehicle and engine manufacturers, highlighting the development processes of hydrogen engines and their applications in passenger and commercial vehicles. Through an analysis of the advantages and limitations of H_2 - ICE, the paper positions H_2 - ICE as a complementary technology to fuel cells (hybrid electric vehicles) and offers specific conclusions and recommendations for future research, including improvements in engine efficiency, emission reductions, and the development of hydrogen infrastructure. These efforts aim to ensure a sustainable and economically viable transition toward clean transportation.

Keywords: *Hydrogen internal combustion engines (H_2 - ICEs); Transport decarbonization; Fuel cells; Emission regulations; Sustainability trends*

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1. Introduction

The energy transition is one of the most significant challenges facing global society. According to the Paris Agreement [1], all United Nations member states have committed to taking necessary steps to limit the rise in emissions of harmful pollutants, maximize the optimization of energy resource utilization, and initiate the use of renewable energy sources by 2030. By 2050, they are expected to achieve climate neutrality, meaning national energy sectors should be fully decarbonized and equipped to rely entirely on renewable energy sources. Globally, the most significant issue stemming from the energy sector is the increase in anthropogenic greenhouse gases (GHGs), which are responsible for the rise in global temperatures compared to pre-industrial levels [2]. Anthropogenic GHGs are gases capable of absorbing and re - emitting thermal energy, contributing to elevated atmospheric temperatures. The types of gases classified as anthropogenic GHGs were identified and defined in Kyoto in 2007, and the most prevalent in Earth's atmosphere include vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone [3]. If current energy exploitation practices continue, it is projected that global temperatures will increase by more than 2 °C, exceeding the targets established by the Paris Agreement [4]. This global temperature rise negatively impacts microclimatic changes, glacier melting, flora, and fauna, which is why efforts are being made to limit the increase in global temperatures to below 1.5 °C [5].

The primary sources of anthropogenic greenhouse gas emissions are the power generation industry, heating plants, transportation, and manufacturing industries, which collectively account for approximately 76 % of total greenhouse gas emissions. The remaining 24 % originates from agriculture and general land use practices [6]. The transportation sector (both passenger and freight) contributes around 20 % of anthropogenic greenhouse gas emissions, with carbon dioxide (CO_2) being the predominant emission [7].

In addition to greenhouse gases, which significantly impact global warming, the transportation sector also emits other types of gases and compounds with adverse local environmental effects, particularly on human health. The most prominent among these are nitrogen oxides (NOx), carbon monoxide (CO), particulate matter (PM), and volatile organic compounds (VOCs) [8]. These substances are especially harmful to human health, contributing to chronic respiratory diseases, including severe conditions such as lung cancer [9]. The emission of these gases and particles arises from the combustion of fossil fuels, the primary energy source for the transportation sector [10]. According to the European Commission [11], adopting renewable energy sources in the transportation sector is essential to reduce global and local impacts. The energy transition in the transportation sector is being implemented in three phases. The first phase involves improving the efficiency of fossil fuel usage in existing systems, primarily by increasing the energy efficiency of internal combustion engines, which currently dominate the sector. The second phase includes using biofuels as a substitute for fossil fuels to reduce the emissions of harmful particles generated during combustion, i.e., the transformation of the chemical energy of fuel into thermal energy and useful vehicle work. The third phase involves a complete transition to alternative energy sources, replacing fossil fuels as the primary energy carrier for transportation operations [12].

The optimization of internal combustion engines has largely reached its limits in terms of energy efficiency [13]. Engine devices and equipment designed to reduce the emission of harmful particles can shorten the lifespan of certain engine components and increase maintenance costs. Alternative energy sources in transportation are increasingly utilized today, primarily through electric vehicles. However, electric vehicles in this context assume "green electricity," meaning electricity derived from renewable sources and used to power transportation systems [14]. In less developed countries, where electricity is predominantly generated from fossil fuels, such as Bosnia and Herzegovina, replacing internal combustion engine (ICE) vehicles with electric vehicles would increase emissions of harmful components into the atmosphere. Another critical issue that would arise is the increased electricity consumption, further straining the power supply system, which could eventually collapse or fail to meet the demand for electricity [15]. For these reasons, the focus has shifted towards transportation systems capable of independently generating electricity and storing it in vehicle batteries rather than solely relying on charging from the power grid. The transition to green energy in the context of air quality is also a significant research topic. For example, a study [16] addresses the current issue of "green" logistics emissions of harmful substances in road transport. It explores the main approaches to reducing emissions, including technical improvements to vehicles and city administrative and organizational traffic planning. In a similar context, a study [17] analyses air quality in Sarajevo in relation to sustainable development goals (SDGs), particularly SDG 11, focusing on PM2.5 particle concentrations and comparing them to European cities. The results highlight the significant impact of air quality on sustainable development and emphasize the need for pollution control measures, especially considering Sarajevo's inclusion on the list of "100 Cities with Net - Zero Emissions" since 2021.

Hybrid vehicles powered by a combination of an internal combustion engine (ICE) and an electric motor are increasingly used and have received highly positive feedback from users regarding efficiency, fuel consumption, and maintenance costs [18]. However, the primary drawback of hybrids lies in the ICE component, which possesses poor environmental characteristics. A study [19] analyses atmospheric pollution caused by thermal engines in hybrid vehicles, presenting experimental results of exhaust gas emissions measured with precision instruments. The study evaluates pollution levels during mixed - route testing, employing eco - driving techniques and advanced electronic control systems for hybrid vehicles, and concludes with a detailed assessment of their environmental impact and ecological viability. In this context, the development of alternative propulsion vehicles has advanced toward those utilizing fuel cells to produce the electricity required for vehicle operation. The combination of fuel cells, where electricity is generated through the electrolysis of hydrogen (H_2), has been the subject of research over the past 15 years, with prototypes developed by various manufacturers [20]. Hydrogen as a fuel is particularly attractive in this context for three key reasons: first, the potential for its technological production from renewable energy sources; second, its neutral impact in terms of emitting harmful substances into the atmosphere; and third, its high calorific value, making it a potential energy source for transportation systems [21]. The main challenges associated with fuel cells and using hydrogen as a fuel lie in storage and transport due to its characteristics [22]. Hydrogen is a chemical compound that can be stored or transported in gaseous or liquid states. The most economical method of transporting hydrogen is in its liquid state, as in its gaseous form, it must be compressed to approximately 700 bars [23]. Liquid hydrogen is also highly unstable due to its sensitivity to elevated temperatures. Hydrogen must be maintained at a temperature of - 253 °C for safe transport in liquid form, which requires substantial energy resources to achieve and sustain this temperature [24].

The challenges above related to the storage and transport of hydrogen (H_2) have slowed its implementation in the mass production of fuel cell vehicles. Consequently, vehicle manufacturers have shifted their focus toward developing fully electric vehicles and hybrids combining internal combustion engines (ICE) with electric motors [25 - 26]. However, energy sector developments have highlighted the issue of the sustainability of electric vehicles and the reliance on renewable energy sources for electricity generation. In response, many countries have restarted or intensified electricity production using fossil fuels. These global disruptions have had a profoundly negative impact on the automotive industry, particularly in Europe. As a solution to this crisis, the intensification of hydrogen - powered vehicle development has been recognized in two directions: the use of H_2 in fuel cells for electric vehicle propulsion and vehicles with internal combustion engines utilizing hydrogen as an energy source for heat release and useful work production. Supporting this approach, a partnership between global leaders in passenger vehicle manufacturing, BMW and Toyota, was established. The two companies signed a collaborative agreement to develop passenger cars equipped with fuel cells that use hydrogen. Their goal is to achieve the mass production and sale of fuel - cell electric vehicles by 2028 [27].

Previous research on applying hydrogen (H_2) as a fuel in internal combustion engines (H_2 - ICE) has focused on analyzing the combustion process, optimizing engine characteristics, reducing harmful gas emissions and noise, and identifying technical challenges. Particular attention has been given to the impact of key parameters such as the air - to - fuel stoichiometric ratio, ignition timing, and exhaust gas recirculation (EGR) on the efficiency and environmental characteristics of the engines. In addition to experimental research, developing predictive combustion models has made significant contributions, enabling more accurate process predictions and further optimization. A study [28] investigates the combustion characteristics and emissions of H_2 - air mixtures in a constant - volume combustion bomb, analyzing the effects of initial conditions, excess air, and dilution on flame propagation and gas emissions. The study found that stoichiometric conditions ($\lambda = 1$) result in the highest temperatures and NOx emissions, while nitrogen (N_2) dilution and combustion under lean conditions significantly reduce emissions and maintain combustion stability. It is recommended to use a 10 % nitrogen dilution and an excess air coefficient of 1.8 – 2.5 to optimize H_2 - ICE performance. A study [29] explores the application of H_2 as a fuel in H_2 - ICE for the decarbonization of heavy - duty vehicles, analyzing the benefits, challenges, and technological requirements. A study [30] examines noise emissions during H_2 combustion in ICE, using statistical analysis and machine learning to identify key factors for reducing noise and preventing knock. It was found that increasing the excess air coefficient (λ), adjusting the ignition timing, and optimizing the exhaust gas recirculation (EGR) rate significantly reduce combustion noise and the tendency for knocking, with λ being the most effective parameter, potentially reducing noise by up to 20 dB.

A study [31] develops and validates a predictive combustion model for hydrogen internal combustion engines (H_2 - ICE), utilizing an improved approach for determining flame propagation velocity. Experimental data collected from a single - cylinder engine were analyzed to evaluate the impact of various calibration parameters, such as the fuel - to - air mixture, exhaust gas recirculation, and pressure. The findings concluded that the model provides high accuracy in predicting combustion processes and has the potential for expansion to include knock modelling and cyclic variability. A study [32] investigates the effect of the air - to - fuel stoichiometric ratio and ignition timing on the performance and emissions of a four - cylinder H_2 - ICE. Results show that reducing the air - fuel equivalence ratio increases effective pressure, thermal efficiency, and combustion velocity while increasing heat losses. Moreover, increasing this parameter reduces NOx emissions, with emissions becoming minimal under certain lean combustion conditions. The study highlights the importance of adjusting ignition timing to ensure combustion stability and emission reductions in H_2 - ICE. Study [33] provides a comprehensive overview of the use of hydrogen as a fuel for H_2 - ICE, covering production methods, emission reduction strategies, and technical challenges. It analyses the advantages and limitations of H_2 - ICE compared to other technologies, such as fuel cells and battery - electric vehicles. The objective of this paper is to review existing technologies and research outcomes related to the application of hydrogen as a fuel for internal combustion engines, to analyze the relevant regulations governing this field, to examine trends among ICE manufacturers, and to offer recommendations for future research and development in this area. This review synthesizes the latest available academic and technical literature concerning H_2-ICEs, with particular focus on their environmental impact, efficiency, and industrial deployment. The selection of sources was limited to the period between 2010 and 2024 to ensure coverage of the most recent advancements, regulatory developments, and industrial demonstrations. Priority was given to peer - reviewed scientific articles, technical reports from established manufacturers, and documents published by regulatory and standardization authorities. Sources were included based on their relevance to the core themes of the review: hydrogen combustion technology, emission control, fuel system integration, and decarbonization potential in transport applications.

2. European Strategies and Regulations for Hydrogen and Transport

This chapter presents the most significant European strategies and regulations regarding hydrogen (H_2) use in the transportation sector. All strategies and regulations concerning H_2 in Europe are based on the Hydrogen Strategy adopted by the European Parliament, which is part of the EU Green Deal strategy and REPowerEU plan [34]. According to this strategy, by the end of 2030, member states are required to implement necessary reforms and transformations in the energy sector, including transportation, to reduce GHG emissions by 55 % compared to 1990 levels and fully decarbonize the energy sector by 2050 [35 - 36]. Within the agenda defined for 2030, 17 main development goals have been outlined as part of the UN Sustainable Development Goals (SDGs) initiative [37]. Four SDG goals are directly related to the transportation sector: 3 - Good Health and Well - being; 7 - Affordable and Clean Energy; 11 - Sustainable Cities and Communities; and 13 - Climate Action. Global changes in energy flows and the economic consequences of the war in Ukraine have necessitated an accelerated energy transition process. In response to these global changes, the EU introduced the REPowerEU Plan, whose primary goal is to expedite green transition processes, to increase energy production from renewable sources, and to achieve energy independence from Russian gas, which includes the production and use of H_2 [36]. Regarding the production of green hydrogen (G - H_2), the European strategy encourages steps to significantly increase electrolyzer capacity, targeting a total capacity of 40 GW by 2030. This plan entails integrating H_2 with renewable energy sources through electricity used in electrolyzers to break water (H_2O) into H_2 and oxygen (O_2), thereby reducing dependence on fossil fuels [36]. The production of G - H_2 is overseen by the European certification system, CertifHy, which aims to standardize and monitor H_2 production and distribution. Figure 1 illustrates the interrelationship between various strategies and sectors to decarbonize the transportation sector. It is evident that the key to this success lies in the synergy between policy, economics, and industry, as well as their mutual collaboration [38].

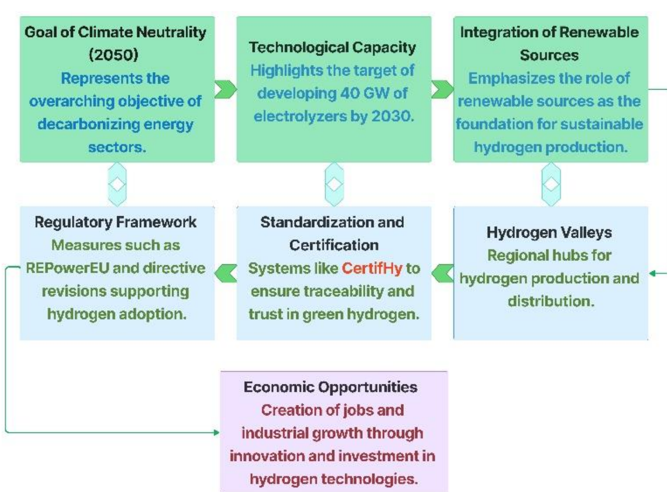

Figure 1. The synergy between technological innovation, econ omic investment, and policy regulation in enabling hydrogen - based decarbonization of transport.

2.1. Emerging Emission Standards (Euro 7/CARB 2027) and the Future of ICE Development

In September 2023, the European Council (EC) adopted the Euro 7 standard (initially proposed in November 2022) to reduce pollutant emissions, with implementation expected in 2028. Generally, the Euro 7 standard has not significantly altered emission limits for exhaust gases. Still, it has introduced substantial changes and restrictions concerning particulate emissions from tyre wear, particles generated during braking processes, and limitations related to electric vehicle batteries and vehicle lifespan (age and mileage). Another significant change lies in the methodology for measuring emissions, which will now be conducted on vehicles under real - world operating conditions [39]. Regarding exhaust gas emissions from internal combustion engines (ICE), the Euro 7 standard mandates identical requirements to the Euro 6 standard for passenger vehicles while introducing additional requirements for heavy - duty vehicles compared to the previous standard. This indicates that ICEs will remain indispensable for heavy - duty vehicles (trucks and machinery) for the foreseeable future, although the demands regarding pollutant emissions will continue to increase [40]. The Euro 7 standard represents a critical turning point for vehicle manufacturers in shaping the future strategies of the automotive industry. For passenger vehicles, manufacturers will focus on producing electric vehicles, which implies the development and production of hybrid electric vehicles with hydrogen fuel cells. In the heavy - duty vehicle sector, the development of ICEs will continue; however, due to increasingly stringent exhaust gas emission regulations, efforts will shift toward exploring alternative fuels, among which hydrogen holds significant potential [41].

Beyond Europe, California's CARB 2027 standards target a 90 % reduction in NO_x emissions from heavy - duty engines by 2027, under the Advanced Clean Trucks Rule and Heavy - Duty Omnibus Regulation. These regulations also extend emission compliance durability to 800,000 km and introduce low - load cycle testing, creating pressure for advanced NO_x control technologies in ICE platforms.

In China, the China VI - b standard, implemented nationally in 2023, mandates real - driving emission (RDE) compliance, tighter particle number (PN) thresholds, and stricter cold - start emissions performance. These requirements, managed by the Ministry of Ecology and Environment, aim to align heavy - duty vehicle regulations with global best practices while supporting regional hydrogen demonstration programs, particularly in freight and transit sectors.

Japan's regulatory framework integrates hydrogen into its national energy transition through detailed technical standards under its High - Pressure Gas Safety Act and Hydrogen Roadmap. While fuel cell vehicles are prioritized in light - duty transport, hydrogen combustion engines are increasingly supported for rail, maritime, and construction applications, especially under the Green Growth Strategy promoted by METI.

In India, Bharat Stage VII (BS7) emission norms, anticipated after 2027, are expected to incorporate elements of Euro 7 and China VI, with specific adaptations for subcontinental climate and operating conditions. India's automotive roadmap emphasizes hydrogen use in long - haul freight, with pilot H_2 -

ICE deployments backed by NITI Aayog's Hydrogen Mission and national OEMs like Ashok Leyland and Tata Motors.

These converging but regionally nuanced regulatory trends suggest a bifurcated technological pathway: passenger vehicles will increasingly transition to battery electrification and fuel cells, while heavy - duty sectors will depend on highly optimized internal combustion engines, especially hydrogen - powered variants.

2.2. Norms For the Safety and Storage Of H_2 In Vehicles

One of the significant challenges in using H_2 as a fuel lies in its storage, transportation, and refueling due to its flammable properties when in contact with air. To prevent accidents during the handling of H_2, whether in gaseous or liquid form, specific Hydrogen Refueling Standards & Regulations (HRSR) have been established [42]. The International Standards Organization (ISO) and the International Electrotechnical Commission (IEC) are the principal global organizations responsible for publishing standards. In collaboration with the Society of Automotive Engineers (SAE), they publish and delegate standards related to the automotive industry down to National Standards Bodies (NSBs) responsible for implementation. The most critical standards for the production, safety, handling, and use of H_2 in the transportation sector are defined through publications determined by Technical Committees. A Technical Committee (TC) is a group of eminent experts who provide specific recommendations and guidelines within a given field, shaping them into standards. Some of the most important TCs related to the use of H_2 in the transportation sector include ISO TC 197, ISO/TC 220, ISO/TC 58; ISO/TC 22/SC 41; IEC/TC 31; IEC/TC 69 and IEC/TC 105 [43 - 49].

3. Technological Basics of Hydrogen Internal Combustion Engines (H_2 - Ice)

3.1. Characteristics of Hydrogen as A Fuel for IC Engines

The properties of hydrogen (H_2) differ significantly from those of conventional fossil fuels. These specific characteristics directly influence changes in internal combustion engine design and technological development. Key properties of H_2, compared to other fuels, have a substantial impact on engine characteristics, energy efficiency, and exhaust gas emissions. Table 1. presents the basic properties of hydrogen in comparison with hydrocarbon fuels [51].

At atmospheric pressure and a temperature of 273 K, the density of H_2 is extremely low, even lower than that of natural gas. This low density is associated with the small molecular weight of H_2. Hydrogen has the highest energy - to - mass ratio among all chemical fuels, making it energetically superior. However, the low - density results in lower volumetric energy content of the fuel - to - air mixture within the engine cylinder, which may lead to reduced power output. This issue can be partially mitigated by direct injection of hydrogen when the intake valve is closed, increasing the energy density of the mixture in the cylinder. Compressing H_2 to high pressures, such as 350 bar, significantly increases its density to 31 kg/m³, while its volumetric energy content rises to 3700 MJ/m³.

These characteristics facilitate the efficient use of H_2 as a fuel, particularly in applications requiring high energy density. The high diffusivity of hydrogen enables rapid homogenization of the fuel - to - air mixture, resulting in better combustion and greater process stability.

Hydrogen has an extremely low minimum ignition energy (0.02 mJ), less than required to ignite a gasoline - to - air mixture. Due to this very low ignition energy, a low - energy spark is sufficient to initiate combustion. This allows combustion even with very lean mixtures but increases the risk of uncontrolled ignition caused by hot spots in the combustion chamber. Given the wide ignition range of hydrogen (4 – 75 % volume in air), the engine can operate with various fuel - to - air ratios, including very lean mixtures, contributing to increased thermal efficiency and reduced emissions. The auto - ignition temperature of hydrogen is relatively high, enabling the use of higher compression ratios without the risk of premature ignition. This and a high - octane number provide greater resistance to knocking than fossil fuels. However, the high flame propagation velocity of H_2 makes it suitable for approaching the ideal thermodynamic combustion process in internal combustion engines. The short quenching distance of H_2 (0.6 mm) means that the flame approaches the cylinder walls before extinguishing, increasing heat losses and potentially affecting particle formation due to oil evaporation, particularly in direct combustion engines [52 - 66].

3.2. Application of Hydrogen in IC Engines

Hydrogen (H_2) can be used as a fuel in internal combustion engines (ICEs) with both spark - ignition and compression - ignition systems, each requiring specific adaptations to achieve optimal performance and harness the benefits of H_2 as a fuel. H_2 demonstrates significant potential in spark - ignition engines due to its unique characteristics, such as rapid flame propagation, low ignition energy, and a wide ignition range, enabling operation with very lean mixtures. One advantage of H_2 in spark - ignition engines is its ability to combust ultra - lean mixtures, resulting in lower flame temperatures, reduced heat losses to cylinder walls, higher thermal efficiency, and decreased NOx emissions. Additionally, emissions of hydrocarbons and carbon monoxide are nearly negligible, with the small amounts generated primarily from the combustion of thin lubricant oil films on cylinder walls. In compression - ignition engines, H_2 offers better efficiency than gasoline engines, especially under partial load conditions. However, the high combustion temperatures at stoichiometric air - to - fuel ratios often lead to increased NOx emissions, necessitating technologies such as exhaust gas recirculation (EGR) or additional cooling measures, like water injection into the intake manifold. Spark - ignition engines are not ideal for applications requiring high torque at low speeds. In such cases, preference is typically given to engines with higher compression ratios, such as compression - ignition engines.

In compression - ignition engines, hydrogen is typically used as an additive to diesel fuel due to its high autoignition temperature, which makes direct combustion in diesel engines challenging. Introducing H_2 into the intake air improves the homogeneity of the mixture thanks to hydrogen's high diffusivity, resulting in reduced emissions of hydrocarbons, carbon monoxide, and carbon dioxide. In these engines, H_2 is usually injected directly into the cylinder at high pressure, with the design of the injection nozzles playing a crucial role in controlling the injection pattern and distribution of H_2 within the combustion chamber. Combined systems, where hydrogen is used as the primary fuel and a small amount of diesel (10 % – 30 %) serves as a pilot fuel to initiate combustion, enable efficient combustion and significantly reduce CO_2 emissions.

Table 1. Hydrogen properties compared with gasoline, diesel, and methane [51, 76]

Property	Hydrogen	Methane	Gasoline	Diesel
Carbon content (mass %)	0	75	84	86
Lower (net) heating value (MJ / kg)	119.9	45.8	43.9	42.5
Density (at 1 bar & 273 K; kg / m³)	0.089	0.72	730-780	830
Volumetric energy content (at 1 bar & 273 K; MJ / m³)	10.7	33.0	$33\ 10^3$	$35\ 10^3$
Molecular weight	2.016	16.043	110	170
Boiling point (K)	20	111	298-488	453-633
Auto - ignition temperature (K)	853	813	623	523
Minimum ignition energy in air (at 1 bar & at stoichiometry; ml)	0.02	0.29	0.24	0.24
Stoichiometry air / fuel mass ratio	34.4	17.2	14.7	14.5
Quenching distance (at 1 bar & 298 K at stoichiometry; mm)	0.64	2.1	2 – 3.5	2.5–4
Laminar flame velocity in air (at 1 bar & 298 K at stoichiometry; m / s)	1.85	0.38	0.37-0.43	0.37-0.43
Diffusion coefficient in air (at 1 bar & 273 K; m² / s)	$8.5\ 10^{-6}$	$1.9\ 10^{-6}$	-	-
Flammability limits in air (vol %)	4-76	5.3-15	1-7.6	0.6-5.5
Adiabatic flame temperature (at 1 bar & 298 K at stoichiometry; K)	2480	2214	2580	2300
Octane number (R + M) / 2	130 +	120 +	86-94	-
Cetane number	-	-	13-17	40-55

However, challenges include regulating NOx emissions, which are increased due to high combustion temperatures, necessitating the use of EGR or water injection to cool down the mixture.

While spark - ignition engines are adaptable without major construction modifications, compression - ignition engines require more advanced technical solutions to ensure hydrogen's efficient and safe application. Nevertheless, both engine types offer significant environmental benefits, including reduced greenhouse gas emissions and the potential to use H_2 as a fuel, making them a key part of the transition to sustainable energy systems. Technological advancements, such as advanced injection systems and NOx reduction strategies, will further enhance the use of H_2 in internal combustion engines, particularly when combined with policies supporting renewable energy and the development of infrastructure for hydrogen storage and distribution.

3.3. Characteristics and Emissions of H_2 - ICE

Hydrogen in internal combustion engines (H_2 - ICE) offers significant potential for improving performance characteristics and reducing hydrocarbon emissions and their compounds. Depending on the mixture ignition method, hydrogen affects engine parameters differently, providing specific advantages and challenges. To quantify the mixture condition, the air to fuel equivalence ratio (λ) is used, defined as:

$$\lambda = \frac{\left(\frac{A}{F}\right)_{actual}}{\left(\frac{A}{F}\right)_{stoich.}} \quad (1)$$

where (A / F) represents the mass - based air to fuel ratio. For hydrogen combustion, the stoichiometric ratio is approximately 34:1, which is significantly higher than for hydrocarbon fuels, enabling leaner operation and reduced CO / HC emissions.

In spark - ignition (SI) engines, hydrogen enables higher thermal efficiency (both indicated and effective) due to its fast flame propagation and wide ignition limits, contributing to more complete combustion. However, the increased adiabatic flame temperature often leads to higher NOx emissions, although lean mixtures can mitigate this effect. Additionally, H_2 eliminates emissions of carbon monoxide (CO), unburned hydrocarbons (HC), and carbon dioxide (CO_2) as it contains no carbon, making it a cleaner alternative to conventional fuels. In compression ignition (CI) engines, hydrogen is typically introduced alongside diesel fuel to enhance air - fuel mixing, leveraging hydrogen's high diffusivity. This results in reduced CO, HC, and CO_2 emissions, as these compounds appear only in trace amounts due to the combustion of lubricating oil. The high energy content of

H_2 contributes to greater thermal efficiency and engine power, although precise tuning of operating conditions, such as injection timing and air - fuel ratios, is crucial for optimal performance. Table 2. and Table 3. data illustrate the impact of H_2 on specific engine characteristics and emissions for spark - ignition and compression - ignition engines. Table 2. provides an overview of hydrogen's influence on the characteristics and emissions of SI engines based on data collected from a literature review. An analysis of the data presented in Table 2. reveals that introducing H_2 as a fuel in internal combustion (IC) engines with spark ignition (SI) significantly enhances engine performance, particularly in terms of thermal efficiency (BTE/ITE) and mean effective pressure (BMEP/IMEP). These effects become more pronounced with higher H_2 fractions in the mixture and optimal engine operating parameters. Adding H_2 also increases engine power while significantly reducing carbon compound emissions, including CO, CO_2, and HC, owing to the absence of carbon in hydrogen. Furthermore, it is notable that several studies report improved cyclic stability and reduced combustion duration at higher hydrogen fractions, which indirectly contributes to lower heat losses and increased thermal efficiency. The increased effective work output observed in these cases suggests a shift in the energy balance toward useful mechanical energy, implying more favorable in - cylinder thermodynamic conditions. In some cases, the introduction of hydrogen also enables stable engine operation at lower equivalence ratios, where conventional fuels would misfire or suffer from incomplete combustion, further amplifying its efficiency benefits. However, the higher proportion of hydrogen often results in increased NOx emissions due to elevated combustion temperatures and faster flame propagation. This challenge necessitates precise control of operating parameters to reduce NOx emissions, especially under higher engine loads.

Table 3. presents the effects of H_2 on the characteristics and emissions of compression - ignition (CI) engines, also based on findings from literature studies. The data in Table 3. indicate that adding H_2 to the fuel in compression - ignition (CI) engines improves thermal efficiency (BTE) across all operating conditions, except in scenarios where efficiency decreases at higher engine speeds and loads.

Table 2. Characteristics and emissions of engines with spark - ignition (SI) using hydrogen

Engine Specification	Fuel Blend	H_2 Fraction	Working Conditions	Performance	Emissions
4 - cyl., inline, CR 12:1 **[70]**	Pure H_2	–	3600 rpm, SI, 2 – 15° BTDC	–	NOx ↑ with rpm; CO_2 / CO / HC: –
1 - cyl., 4 - stroke, H_2 DI, gasoline PFI **[71, 75]**	Ethanol + H_2	5 %, 10 % vol.	1500 rpm, 4.4 kW	BTE/ITE ↑, BMEP ↑, Power ↑ (λ ↑)	NOx ↑; CO_2 / CO / HC ↓
6 - cyl., inline, CR 11.5:1 **[72]**	CNG + H_2	%, 20 %, 40 %	177 kW, 2300 rpm	BTE ↑	NOx ↑; CO_2 / CO / HC ↓
6 - cyl., inline, CR 10.5:1 **[73]**	CNG + H_2	0 %, 20 %	154 kW, 2800 rpm	–	NOx ↓ vs. CNG; CO_2 / CO / HC ↓ vs. CNG
4 - cyl., 1.8L, gasoline PFI + H_2 DI **[74]**	Gasoline + H_2	3.9 – 10.5 %	1500 rpm, λ = 1.0 – 1.8, 120° BTDC	BMEP ↑ (λ = 1.8, advanced timing)	NOx ↑; CO_2 / CO / HC ↓

Table 3. Characteristics and emissions of engines with compression ignition (CI) using hydrogen

Engine Specification	**Fuel Blend**	**H_2 Fraction**	**Test Conditions**	**Performance**	**Emissions**	**Particulates**
6 - cyl., DI, turbocharged **[77]**	Diesel + H_2	0 %, 0.6 %, 1.2 %	0 – 100 % load, 800 – 1840 rpm	BTE ↑ (all loads)	NOx: ↑ (med/high load), ↓ idle/low); CO_2 / CO ↓; HC ↑ (excl. idle)	–
4 - cyl., 2.0L TDI **[78]**	Diesel + H_2	0 %, 25 %	15 – 45 % oad, 2000 –3000 rpm	Efficiency ↓ (most loads / rpm)	CO_2 ↓; CO comparable; HC ↓	PM number ↓
1 - cyl., 1.3L modified **[79]**	Diesel + H_2	0 – 90 %	600 – 1500 rpm	ITE ↑ (high load), IMEP ↑	NOx: ↓ (low load), ↑ (high); CO_2 / CO / HC ↓	Soot ↓
1 - cyl., CR 19:1 **[80]**	Diesel + H_2	0 %, 30 %	1100 rpm, 40 – 100 % load	BTE ↑	NOx / CO_2 / CO ↓; HC ↑	Smoke ↓
1 - cyl., 0.3L CI **[81]**	D, D + BD,) + BD + H_2	0 %, 10 %, 30 %	20 – 100 % load	BTE / Power ↑ (D + BD + H_2 vs. D + BD)	NOx ↑; CO_2/CO/HC ↓ (vs. D / D + BD); Smoke / Soot ↓ (vs. D / D + BD)	–

Increasing the share of H_2 in the fuel generally contributes to a reduction in CO_2, CO, and HC emissions, resulting from hydrogen combustion without carbon, while smoke and soot emissions also decline, especially when a mixture of diesel, biodiesel, and hydrogen is used. However, NOx emissions increase under higher loads and with specific fuel mixtures due to the elevated combustion temperatures caused by the presence of hydrogen. The impact of H_2 on particulate matter (PM) emissions shows a decrease in particle numbers across all engine operating conditions. Overall, adding H_2 positively influences the reduction of carbon - based emissions and particulates while improving engine efficiency, though it also leads to higher NOx emissions.

In CI engines, hydrogen enrichment also appears to reduce ignition delay, leading to a more controlled and timely combustion process, which helps minimize unburned fuel fractions. Some configurations show reduced brake - specific energy consumption, suggesting that hydrogen facilitates a more efficient pressure rise and combustion phase, again indicating reduced heat rejection to the chamber walls. While a complete heat balance was not conducted in this review, the consistent increase in thermal efficiency and reduction of incomplete combustion products across sources indirectly support the hypothesis of lower relative thermal losses when hydrogen is employed.

Tables 2 and 3 present summarized data from multiple peer - reviewed studies related to hydrogen substitution in IC engines. Each dataset is accompanied by the corresponding reference in the table to ensure traceability. Although the primary goal of this paper is to provide an overview of hydrogen use in ICEs, it is important to acknowledge that the results and conclusions may be influenced by several sources of uncertainty. These include assumptions related to combustion models, fuel composition, engine control parameters, and measurement inaccuracies. A detailed uncertainty quantification was not conducted, but future work should focus on a comprehensive sensitivity and error propagation analysis to further validate the presented findings.

3.4. Efficiency of H_2 - ICEs Compared to Fuel Cells

Fuel cell electric vehicles (FCEVs) utilize electrochemical conversion to transform hydrogen into electricity, achieving system efficiencies exceeding 60 % while emitting only water vapor. However, widespread commercialization faces barriers including elevated manufacturing expenses and stringent purity requirements (> 99.97 % H_2) to prevent membrane degradation [51]. Hydrogen - fueled internal combustion engines offer a transitional solution for hard - to - electrify transport sectors, particularly in heavy machinery and long - haul applications [84]. This technology provides distinct advantages by leveraging existing ICE manufacturing infrastructure and requiring lower hydrogen purity thresholds compared to FCEVs [50].

While H_2 - ICEs demonstrate approximately 20 - 25 % lower well - to - wheel efficiency compared to fuel cell electric vehicles (FCEVs), they offer distinct advantages in certain applications. The combustion process in H_2 - ICEs generates NOx emissions due to high - temperature oxidation of atmospheric nitrogen, whereas FCEVs emit exclusively water vapor. This fundamental difference stems from their respective energy conversion mechanisms - electrochemical versus thermochemical processes.

From a maintenance perspective, H_2 - ICEs retain the mechanical complexity of conventional internal combustion architectures, requiring periodic servicing of moving components. In contrast, FCEVs employ solid - state energy conversion with fewer wearing parts, though their dependence on lithium - ion battery systems introduces separate challenges. Current analyses indicate battery production accounts for 30 – 40 % of FCEV manufacturing costs and carries significant mineral extraction impacts. The purity threshold divergence presents another key differentiator: FCEVs demand hydrogen purity ≥ 99.97 % to prevent catalyst poisoning, while H_2 - ICEs can tolerate impurities up to 5 % without significant performance degradation. This operational flexibility enables H_2 - ICEs to utilize hydrogen from diverse production pathways, including byproduct streams from industrial processes. These complementary characteristics create a technological synergy where: FCEVs excel in light - duty applications demanding zero operational emissions; H_2 - ICEs serve heavy - duty sectors requiring rapid refueling and load flexibility; both technologies drive demand for green hydrogen infrastructure development. This bifurcated approach optimizes the hydrogen transition across different transportation segments while addressing the limitations of singular solutions [67,82,83,85,89].

According to research [88], FCEVs demonstrate nearly twice the tank - to - wheel efficiency compared to H_2-ICEs. In WLTP cycles, hydrogen consumption is approximately 1.05 kg/100 km for FCEVs versus ~1.79 kg / 100 km for H_2-ICEs. Also, H_2-ICEs may produce 2 – 3 times more greenhouse gas (GHG) emissions than FCEVs when using grey hydrogen, primarily due to combustion - related inefficiencies (Table 4.). A well - recognized trade - off exists between these technologies. H_2-ICEs, while benefiting from lower capital and maintenance costs due to their derivation from conventional engines and the reuse of established manufacturing infrastructure, face the challenge of nitrogen oxide (NO_x) emissions formation during combustion. In contrast, FCEVs utilize electrochemical conversion, resulting in zero operational pollutant emissions but requiring entirely new and costly manufacturing supply chains for fuel cell stacks, power electronics, and high-purity hydrogen handling systems.

Although both hydrogen utilization concepts (H_2-ICEs and FCEVs) offer promising pathways for decarbonizing the transport sector, their true environmental impact must be evaluated through a well - to - wheel (WTW) lens, encompassing emissions associated with hydrogen production, storage, and distribution. Lifecycle assessments show that the source of hydrogen is a decisive factor in determining overall greenhouse gas (GHG) emissions.

When hydrogen is produced via steam methane reforming without carbon capture (i.e., grey hydrogen), the WTW emissions of H_2-ICE vehicles can rival or even exceed those of conventional diesel engines, largely offsetting the benefits of zero tailpipe CO_2 emissions [88]. This is due to high upstream emissions from fossil - based hydrogen pathways and energy - intensive compression and transport processes.

Conversely, the use of green hydrogen, generated through electrolysis powered by renewable electricity, can substantially reduce WTW GHG emissions. In such scenarios, H_2-ICEs achieve up to 70 % lower lifecycle emissions compared to diesel vehicles, although still somewhat higher than FCEVs due to their lower tank - to - wheel efficiency, according to A comparative review of hydrogen engines and fuel cells for trucks by the University of California. This highlights that while both technologies can contribute to decarbonization, maximizing their environmental potential depends critically on the hydrogen supply chain's carbon intensity.

Moreover, storage and distribution infrastructure also influence the lifecycle profile. High - pressure gaseous storage and long - distance transport can increase energy demand and associated emissions, particularly for H_2-ICE applications where higher hydrogen quantities are required per kilometer due to lower efficiency. These factors underscore the importance of integrated energy system planning in realizing the full environmental benefits of hydrogen - powered mobility [88].

Table 4. Comparative Overview of H_2 - ICEs and FCEVs [88]

Parameter	H_2 - ICE	FCEV
WLTP H_2 Consumption (kg/100 km)	~ 1.79	~ 1.05
Tank - to - Wheel Efficiency	~ 25 – 40 %	~ 40 – 60 %
NO_x Emissions	Significant (requires control)	None
GHG Emissions (grey H_2)	2 – 3 × higher than FCEV	Very low (zero during operation)
Hydrogen Purity Requirement	~ 99.5 %	≥ 99.999 %
Vehicle Cost / TCO	Lower (uses existing ICE platforms)	Higher (fuel cell stack, electronics)
Technological Maturity	High (based on legacy ICE tech)	Moderate to high

4. Trends Among Vehicle Manufactures

The development of hydrogen combustion technologies dates back to the 19^{th} century, with intensive research and development commencing around 2010 when electric vehicles entered the market. During this period, electric vehicles were presented as fully eco - friendly solutions, but it became evident that the production process for electric batteries is highly detrimental to the environment [86].

The concept of battery - electric vehicles applies to passenger cars. Still, it is not viable for heavy - duty vehicles, machinery, and emergency response vehicles, where internal combustion engines (ICEs) are currently indispensable. In this context, it is necessary to find a fuel whose combustion does not have a negative ecological impact, such as hydrogen (H_2) [51]. Vehicles with internal combustion engines running on hydrogen (H_2 - ICE) can be designed with hydrogen as the sole fuel or with a dual - fuel system (hydrogen and another gas) [67 - 69]. Vehicle manufacturers who were among the first to recognize the potential of H_2 - ICE are also leaders in this field, including Ford, BMW, Mazda, Chevrolet, and Toyota. In the series of innovations aimed at reducing emissions and promoting sustainable development through the use of hydrogen in internal combustion engines (ICE), two solutions based on hydrogen powered ICEs stand out.

One of these focuses on applications in motorsport, while the other provides solutions for decarbonizing the transport sector, particularly heavy - duty vehicles and machinery for demanding off - road conditions. These technologies not only demonstrate the technical potential of hydrogen as a fuel but also offer various perspectives on its practical application, from high - performance track applications to efficient and environmentally friendly transport on roads and off - road. Current activities on the development of internal combustion engines powered by hydrogen can be seen in Figure 2.

AVL's hydrogen - powered ICE (H_2 - ICE) engine was developed as a demonstration of the technological potential for carbon - neutral propulsion in motorsport, using a 2.0 - liter inline four - cylinder engine with a Miller cycle, direct hydrogen injection, and a compression ratio of 10:1. The goal of the project was to achieve a specific power output of 150 kW/l, with a maximum power of 300 kW at 6500 rpm and a torque of 500 Nm between 3000 and 4000 rpm, while the mean effective pressure (BMEP) reached 32 bar in the same rpm range. Innovative technological interventions included water injection to modify the combustion process and reduce NOx emissions, as well as optimization of gas dynamics to reduce thermal losses and the amount of residual gases in the combustion chamber, thereby improving stability and operational efficiency.

Although hydrogen has a low energy density by volume and requires high filling pressures, its poor lubricating ability challenges the reliability of hydrogen direct injection system components.

Modifications to the engine, such as an aluminum intake manifold, special injectors for hydrogen, and an optimized cooling system, ensured high performance on the test bench. After successfully achieving initial goals, further steps involve improving reliability, increasing power, reducing dependence on water injection, and testing in real racing conditions. Led by AVL RACETECH, this project continues to confirm the potential applications of hydrogen engines in motorsport [87].

The MAN H4576 hydrogen engine represents a significant step forward in the decarbonization of the transport sector, especially for heavy - duty trucks and off - road machinery, where CO2 and other pollutant emissions have traditionally been high. Based on the reliable MAN D3876 diesel engine, this hydrogen engine retains 80 % of its core components, including the engine block, crankshaft, and cooling and lubrication systems, allowing easy integration into existing truck chassis and drive systems. By increasing the cylinder bore to 145 mm, the engine's displacement was increased to 16.8 liters to compensate for the lower power density of the hydrogen engine, ensuring a power output of 368 kW and torque comparable to that of conventional smaller displacement diesel engines. Advanced low - pressure direct hydrogen injection technology, with pressures up to 40 bar, combined with an optimized ignition system and a new turbocharger, provides high engine efficiency, while the combustion process is tailored to reduce nitrogen oxide (NOx) emissions to nearly zero. This technology meets the strictest emission standards, enabling its use in urban environments with emission restrictions and in rural and industrial areas. MAN plans to begin serial production of vehicles powered by this engine in January 2026.

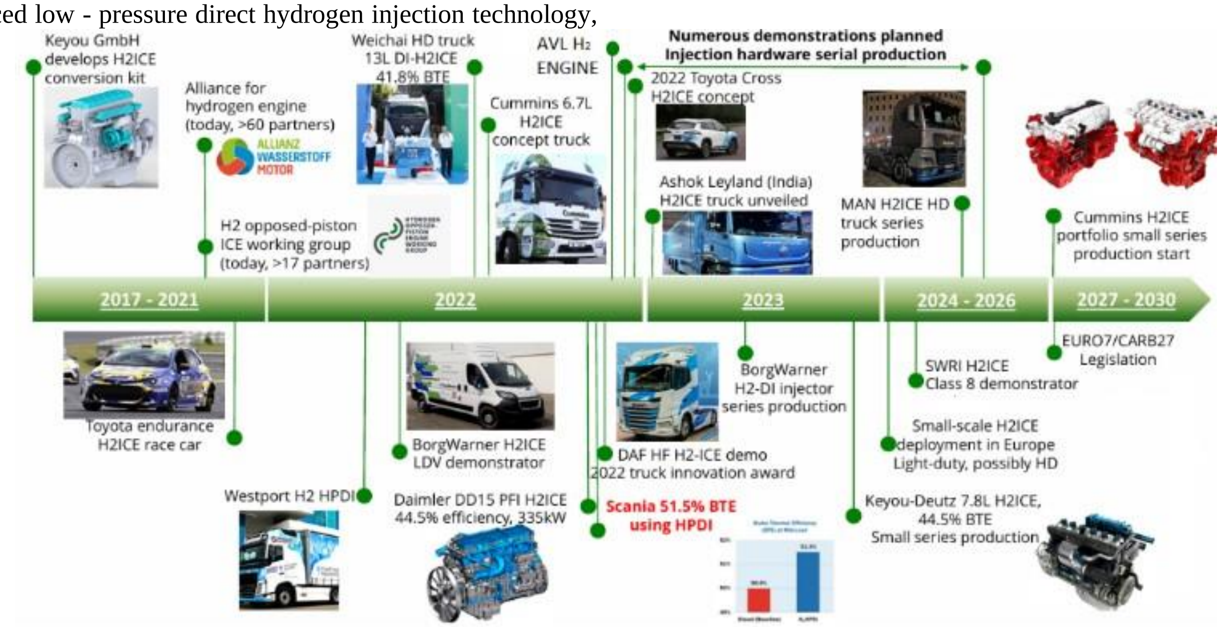

Figure 2. Timeline of the projected development of internal combustion engines powered by hydrogen from 2017 to 2030. Key te chnological milestones and phases of commercial and pilot deployment are illustrated.

5. Conclusions

The application of hydrogen (H_2) in internal combustion engines (H_2 - ICEs) represents a key technology in achieving sustainable development and decarbonizing the transport sector, contributing to global goals and European strategies. This paper highlighted a range of technical, ecological, and economic advantages of H_2 - ICE technology and challenges that manufacturers face in addressing technical limitations in hydrogen combustion, reducing NOx particle emissions at high temperatures, and solving issues related to hydrogen storage and transportation.

Key conclusions regarding modifications to existing IC engines and the characteristics of H_2 - ICEs:

- To enable the application of H_2 - ICE technology, modifications are needed in the fuel supply systems, combustion chambers, and thermal regulation of the engine. This includes developing hydrogen injection systems, controlling the combustion process, and reducing NOx emissions, which are the main byproducts of combustion at high temperatures.
- Special attention needs to be paid to optimizing the stoichiometric ratios of air - to - fuel, exhaust gas recirculation (EGR), and adjusting the ignition timing to reduce emissions and increase the engine's thermal efficiency.

Regulations and safety standards:

- The Euro 7 standard, adopted in 2024 by the European Commission, introduces stricter limits on exhaust emissions and encourages the industry to seriously develop vehicles that will use green hydrogen as fuel in the transport sector.
- Safety measures, defined through global ISO standards and European IEC standards, are critical for the safe transportation, storage, and distribution of hydrogen.

Hydrogen production and storage:

- Green hydrogen (G - H_2), produced from renewable energy sources, represents a key step in decarbonization. The European Union plans to increase the electrolyzer capacity to 40 GW by 2030 to ensure an adequate supply of G - H_2 for industry and transport.
- Hydrogen storage remains a challenge due to its physical and chemical properties. The safest and most efficient transport method is in liquid form at extremely low temperatures (- 253 °C), which requires significant energy investments.

Industrial trends and technology development:

- Vehicle and engine manufacturers such as Toyota, BMW, Mazda, MAN, and Cummins are leading the development of H_2 - ICE technology through research and implementation in both heavy - duty and passenger vehicles.
- The dual use of hydrogen and hydrocarbon fuels, along with the development of fuel cells, enables a more flexible transition to decarbonization, with H_2 - ICE technology serving as a complementary solution alongside electrification.

Despite the growing interest and progress in hydrogen internal combustion engine (H_2-ICE) technologies, several unresolved technical and research challenges remain. These should be addressed to ensure their viability and competitiveness in decarbonizing the transport sector:

- High - temperature combustion of hydrogen leads to the formation of thermal NO_x. Advanced strategies such as lean burn techniques, enhanced exhaust gas recirculation (EGR), and after treatment systems (e.g., SCR) require further optimization and validation under real driving conditions.
- Precise control over hydrogen direct injection timing, pressure, and mixing is essential to achieve efficient combustion while avoiding pre - ignition and knock. Research is needed on multi - point injection systems, stratified combustion modes, and adaptive control algorithms.
- Ensuring reliable engine operation across various ambient conditions, particularly during cold starts and low - load scenarios, remains a critical area for development.
- The high diffusivity and small molecular size of hydrogen can lead to embrittlement of metallic components. Long - term durability studies of engine materials and sealing systems are essential for commercial deployment.
- Although this paper primarily focuses on technical and environmental aspects, future work should include comprehensive techno - economic modeling, comparing total cost of ownership (TCO), infrastructure costs, and market scenarios across H_2-ICE, FCEV, and BEV technologies.

Recommendations for future research:

- Focus on research and optimization of hydrogen storage and distribution systems, emphasizing minimizing energy losses and ensuring safety during transportation.
- Advance the optimization of stoichiometric air - fuel ratios and exhaust gas recirculation (EGR) processes to reduce NOx emissions while maintaining combustion stability and achieving high thermal efficiency.
- Investigate the integration of hydrogen technologies with local renewable energy sources, including the potential for developing green hydrogen production infrastructure to enhance energy sustainability and reduce reliance on fossil fuels.

H_2 - ICE technology is not a universal solution but plays a vital role in the transition to sustainable transport. Its adoption can reduce emissions of pollutants in sectors where vehicle electrification is not currently an optimal solution. Combining H_2 - ICE technology, fuel cells, and hybrid systems represents the most realistic path towards achieving climate goals and sustainability by 2050. Also, future studies should aim to include a detailed heat loss and thermal balance analysis, particularly to assess the impact of hydrogen's high diffusivity and combustion characteristics on wall heat transfer and overall thermal efficiency.

Nomenclature

$w(C)$	: carbon content - mass fraction (%)
LHV	: lower heating value (MJ / kg)
ρ	: density (kg / m^3)
E_v	: volumetric energy content (MJ / m^3)
M	: molecular weight (g / mol)
T_b	: boiling point (K)
T_{ig}	: auto - ignition temperature (K)
E_{min}	: minimum ignition energy (mJ)
$\left(\frac{A}{F}\right)$	: air to fuel ratio
d_q	: quenching distance (mm)
S_L	: laminar flame speed (m / s)
D	: diffusion coefficient (m^2 / s)
φ	: flammability limits - equivalence ratio (% Vol.)
T_{ad}	: adiabatic flame temperature (K)
ON	: octane number
CN	: cetane number
CR	: compression ratio
RPM	: engine speed (min^{-1})
$BMEP$	: brake mean effective pressure (bar)
$IMEP$	: indicated mean effective pressure (bar)
BTE	: brake thermal efficiency (%)
ITE	: indicated thermal efficiency (%)
λ	: air to fuel equivalence ratio
$BTDC$	: before top dead center (°)
DI	: direct injection
PFI	: port fuel injection
P	: power output (kW)
T	: torque (Nm)
η	: efficiency (%)
NO_x	: nitrogen oxides (ppm)
CO	: carbon monoxide (ppm)
CO_2	: carbon dioxide (% Vol.)
HC	: unburned hydrocarbons (ppm)
PM	: particulate matter (mg / m^3)
$Soot$	: solid carbon particles (mg / m^3)
$Smoke$	: particulate visibility (%)

Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal ties that could have seemed to affect the work reported in this study.

CRediT Author Statement

Dževad Bibić: Conceptualization, Supervision,
Ammar Trakić: Conceptualization, Writing original draft, Validation,
Jasmin Šehović: Data curation, Formal analysis

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