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Mariusz J. NIEŚCIORUK
Andrei-Alexandru BOROIU
Gustavo OZUNA
Agustín Brau ÁVILA
Przemyslaw KUBIAK
Marek WOZNIAK
Krzysztof SICZEK

Combustion Engines
Polish Scientific Society of Combustion Engines

The use of hydrogen to supply combustion engines – part 1

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Hydrogen is used to supply various internal combustion engines, as well as to fuel cells, which are employed in various vehicles. The goal of the present study was to review the state of art relative to the application of H_2 in the automotive industry. The review focuses on out-of-engine studies on the effect of H2 combustion processes, internal combustion engines supplied with H_2, and vehicles utilizing fuel cells. Challenges in applying fuel cells to actual vehicles include limited flexibility in controlling power flow in the PEMFC + B setup, significant power flow losses, which complicate the management of energy systems in case of. The PEMFC + B + UC configuration, as well as a low power density of batteries. A drawback of H_2 engines is the emission of NO_x, which can be lowered by exhaust gas treatment. Fuel cell vehicles (FCVs) can be a clean energy alternative to gasoline-powered cars. However, their development depends on H_2 fuel availability and the expansion of refueling infrastructure.

Key words: *hydrogen, combustion engines, fuel cell, exhaust gas emissions*

1. Introduction

Stringent emission standards, with pollution levels closely linked to the combustion quality of existing internal combustion engines (ICEs), force manufacturers to develop new fuel injection solutions and adapt existing ones to meet more stringent standards [13]. Furthermore, other solutions are being sought to meet stringent emission standards. Nowadays, hydrogen (H_2) is increasingly being used to power ICEs in various types of vehicles and stationary applications. The development of the energy and transportation sectors has increased interest in using fuels derived from renewable sources, rather than fossil fuels.

Menes [68] conducted a synthetic review of the political framework, specifically the operational plans and initiatives, along with national leadership for the advancement of H_2 technologies and efficiency in 19 countries.

Gis and Gis [36] explored the circumstances surrounding–the adoption of hydrogen in transportation in Northwestern Europe. Taking into account various technical aspects –including hydrogen refueling stations (HRS) and fuel cell electric vehicles (FCEVs), and economic factors (such as H_2 usage costs), the following countries were included: Belgium, Denmark, France, Germany, the Netherlands, Norway, and England. In Poland, significant fuel and energy corporations (including Orlen, Lotos, PGNiG, and ZE PAK Capital Group) are highly interested in the application of H_2 in transportation, while vehicle manufacturers such as Solaris and Autosan are focused on developing vehicles with fuel cells (FCs). It was discovered that the optimal placement of basic H_2 refueling stations is situated along the TEN-T corridors traversing Poland. The sequence of such locations is as follows: 1 – Poznan, 2 – Warsaw, 3 – Bialystok, 4 – Szczecin, 5 – Łódź region, 6 – Tricity, 7 – Wroclaw, 8 – Katowice region, 9 – Kraków.

Sikora and Orliński [98] observed that on 28 March 2023, the EU Council approved a rule imposing strict CO_2 emission norms for new cars and vans; therefore, from 2035 onward, only electric or H_2-fueled cars and vans will be eligible for registration. Notably, hydrotreated vegetable oil was excluded as a fuel from the Fit for 55 package regarding cars and vans. This type of fuel can replace diesel with HVO fuel without affecting the fuel injection (FI) control system and also has significant potential to reduce greenhouse gas emissions.

Various techniques used for the extraction of H_2 from biomass are reviewed in [74].

Skobiej [99] reviewed the most recent studies and progress in utilizing H_2 as fuel for internal combustion engines. The review thoroughly examined H_2's ability to enhance combustion efficiency, particularly when mixed with NH_3 or CH_4. Essential findings emphasize H_2's potential to reduce detrimental emissions, such as CO, HC, and soot, while it may increase NO_x emissions due to elevated combustion temperatures. The article also examines different H_2 injection methods, such as direct injection (DI), which surpasses port fuel injection (PFI) by notably improving power production and fuel efficiency. Additionally, the research highlights the importance of adjusting H_2 ratios in dual-fuel ICEs to achieve a balance between efficiency and emissions. These findings underscore the importance of H_2 in future decarbonization initiatives, with ongoing studies focused on reducing NO_x emissions while maintaining high efficiency.

Wesołowski et al. [130] suggested producing H_2 through the gasification of electronic waste in a steam environment to create syngas, which can serve as a H_2 source after isolation processes. They showcased the outcomes of gasifying electronic waste, which includes plastic components or epoxy resins, detailing the composition of the syngas produced during recycling and evaluating the possibilities of this waste processing for fueling transportation.

Matla et al. [66] examined the current understanding of H_2 combustion systems, which are now quite popular, primarily because of the advanced production technology and comparatively low recycling costs of FCs. The authors examined existing solutions that address challenges associated with H_2 production, storage, and transport. They stated that the forecasted threefold increase in H_2 production by 2050, driven by decreasing production costs, promotes research focused on its application as a fuel for H_2 ICEs.

Stępień [103] reported that H_2, being a zero-emission fuel, enables the construction of a piston ICE that meets the criteria for "Zero Emission Vehicles" regarding CO_2 emissions. The piston ICE powered by H_2 could serve as a bridging technology for powertrains, particularly in trucks and off-road vehicles, competing with both electric drives and FCs. The author offered a comprehensive examination of the potential advancement and distribution of H_2-fueled ICEs in automobiles.

A separate development group consists of vehicles utilizing hydrogen via FCs, known as fuel-cell electric vehicles (FCEVs) [28], some of which are in the early stages of development. Daszkiewicz and Kołodziejek [24] examined the option of utilizing ultracapacitors, batteries, or FCs to enhance the efficiency of a rail vehicle's powertrain. The choice of the right solution relies on the vehicle's intended purpose and its traction features. Zadrąg et al. [134] simulated dynamic loads on the propulsion system of ships equipped with unconventional power systems – reformed methanol FCs (RMFCs).

The present study reviews the state of art regarding the application of H_2 in the automotive industry. The review focuses on out-of-engine studies on the effect of H2 combustion processes, internal combustion engines supplied with H2, and vehicles powered by FCs.

2. Out-of-engine studies on the effect of H_2 combustion process

2.1. General overview and key mechanisms

Out-of-engine studies on H2 combustion processes are conducted numerically or on test stands, including dedicated burning chambers.

Habib et al. [38] compared various H_2 combustion mechanisms elaborated by various researches, including GR13.0 [116], Dagaut et al. [22], ÓConaire et al. [75], Zsély et al. [138], Davis et al. [25], Saxena & Williams [94], Sun et al. [105], Li et al. [58], Ahmed et al. [2], USC-II [126], Konnov [52], Rasmussen et al. [86], Starik et al. [102], NUIG-NGM [42], Hong et al. [45], SanDiego [21], Burke et al. [18], CRECK [114], Kéromnès et al. [49].

ÓConaire et al. [75] developed a comprehensive kinetic model for H_2/O_2 combustion across a wide range of temperatures (298–2700 K), pressures (0.05–87 atm), and equivalence ratios (0.2–6). This extensive system and evaluation examined combustion characteristics across a range of temperatures, from low to high, and pressures, from subatmospheric to elevated, for fuel-lean to fuel-rich mixtures. Their rigorous assessment provided insights into essential reaction pathways across various combustion conditions, relevant to both basic kinetics and real-world applications.

Li et al. [59] conducted an in-depth analysis of the chemical reaction dynamics for H_2/O_2 combustion, referencing previous research (15) and utilizing new kinetic and thermodynamic data. Their mechanism was tested under various experimental conditions, including shock tubes, flow reactors, and laminar premixed flames. They determined that the H + OH + M reaction is crucial, particularly for simulating high-pressure flame propagation, as flame speeds were matched by employing different transport coefficients from the literature, with adjustments made to the rate within acceptable uncertainty.

The mechanism of the H_2/O_2 reaction is essential for both basic kinetics studies and practical combustion applications such as fire safety, energy conversion, and stimulus [59]. The application of H_2 as a fuel in these sectors requires knowledge of its oxidation chemistry. Moreover, the fundamental reactions involving the species H, O, OH, HO_2, and H_2O_2 are crucial for forming the reactive radical pool that initiates oxidation in HC fuels. Thus, enhancing H_2/O_2 kinetics provides a better understanding of the combustion process and advances H_2-oriented technologies in various sectors [75]. The H_2/O_2 reaction mechanism is explained in [59].

2.2. Recent advances in H_2 combustion chemistry

Recently, several studies have enhanced the comprehension of H_2 combustion chemistry [53]. In the reaction H_2 + OH = H_2O + H, studies [67, 106, 129], showed strong consistency with prior experimental findings. Nonetheless, the discrepancies in the determined rate constants were greater than those used in kinetic models from 2015 [53], making it difficult to choose a revised expression. An experimental investigation conducted between 295 and 701 K on the reaction OH + OH = H_2O + O, which is not part of a [53, 118, 119] H_2 kinetic mechanism, found that the rate constant from the study by Sangwan and Krasnoperov [93] below 834 K was less than other recorded measurements. The low-temperature rate constant was in agreement with the theoretical study conducted by Nguyen and Stanton [72]. Another study [5] suggested a fit to such data, indicating strong alignment with high-temperature tests by Wooldridge et al. [131] and a reverse rate from Sutherland et al. [107]. Hong et al. [44] also supported the findings of Wooldridge et al. [131].

Konnov [52] analyzed recent proposals by Burke and Klippenstein [19, 51] regarding the influence of chemically termolecular reactions, such as H + O_2 + R, on H_2 combustion kinetics under typical conditions. These reactions require careful consideration for inclusion in mechanisms, as they alter reactivity and laminar flame speeds. To investigate this, a comprehensive H_2 combustion mechanism was assessed to mitigate increased chain termination from these reactions while preserving or enhancing model performance. Revised kinetic investigations led to the inclusion of four new reactions and modifications to three rate constants, although this significantly decreased the computed burning velocities compared to experiments and earlier models, primarily due to termolecular reactions. The introduction of a theoretical transport database from Jasper et al. [47, 48] greatly improved the accuracy of the revised model, aligning it closely with experimental burning speed data for H_2+air flames at atmospheric pressure, representing a notable advancement over previous models [54]. The system included new termolecular reactions and revised rate constants for existing reactions. These chemical changes did not significantly affect the mechanism's ability to simulate H_2 self-ignition and oxidation behavior in flow reactor setups.

Olm et al. [76] systematically evaluated 19 H_2 combustion mechanisms using an extensive experimental dataset, including ignition delays, species profiles, and burning speeds. They established error function values to assess the effectiveness of each mechanism across different test datasets, with values closer to one indicating better performance.

According to the average error function values, the Kéromnès [49] mechanism provides the most accurate predictions for ignition delay times and burning speeds, while the flow reactor data was best represented by the Starik [102] mechanism. Overall, the Kéromnès-2013 mechanism demonstrated the highest efficiency, closely followed by NUIG-NGM [42], Konnov [52], and Li et al. [58].

2.3. CFD modeling and engine performance findings

Simulations in computational fluid dynamics (CFD) indicate that DI ICEs achieve a 40% increase in brake power, resulting from a 30.6% improvement in volumetric efficiency. Additionally, DI systems reduce NO_x emissions by 36% compared to port fuel injection (PFI) with H_2 at an optimal air/fuel (A/F) ratio (λ) of 1.5. The research also highlights H_2's superior efficiency in reducing fuel consumption – by 71.8% compared to CH_4 and 67.2% compared to coke oven gas (COG) – due to its higher heating value per unit mass [71]. The significant 71.8% decrease in brake-specific fuel consumption observed with H_2 DI compared to CH_4 is mainly attributed to H_2's higher energy density. The precision of the DI system further amplifies this effect by optimizing the combustion process, minimizing fuel waste, and increasing thermal efficiency. These results were obtained for an optimal A/F ratio ($\lambda = 1.5$), maximizing the benefits of H_2's exceptional combustion properties.

2.4. Influence of H_2 enrichment and combustion strategies

Gharehghani et al. [35] numerically studied the effect of H_2 enrichment on the operational range and combustion characteristics of a spark-ignition (SI) ICE powered by natural gas (NG). They found that misfiring occurred at equivalence ratios of approximately 0.61, 0.48, and 0.42 for H_2 fractions of 0%, 30%, and 50%, respectively. Combustion durations were 70, 47, and 45° crank angle for H_2 contents of 0%, 30%, and 50%, respectively, at the same equivalence ratio ($\Phi = 0.625$). The highest brake-specific NO_x was observed at $\Phi = 0.83$ ($\lambda = 1.2$), and this value was nearly unaffected by the H_2 fraction. Increasing the H_2 fraction reduced emissions of CO, HC, and CO_2. Adding 30% H_2 reduced CO_2 emissions by 10.2%, while a 50% H_2 fraction led to a 22.7% reduction.

Matla et al. [66] proposed a conceptual H_2 combustion system for ICEs, utilizing a prechamber to improve combustion parameters and overall engine efficiency. As noted in [65], a split combustion chamber solution enhances the controllability of the combustion process in H_2 ICEs. Such a system is theoretically more efficient than any previously known solution. It was determined that the compression ratio (CR) and the degree of mixture depletion have the most significant impact on the H_2 combustion process. Their influence on H_2 knock formation was assessed, which can be categorized as severe knock (highly undesirable) or mild knock, depending on the level of pressure oscillations in the combustion chamber; in the latter case, combustion improvement is possible.

Brzeżański et al. [14] studied the combustion of H_2-air mixtures with varying compositions. After H_2 DI was introduced into an isochoric combustion chamber, the mixture formed during the combustion process. The effect of fuel dose distribution before and after ignition on fire front development and pressure behavior in the isochoric chamber was analyzed. Management of the H_2-air mixture's combustion, primarily related to flame front velocity and heat release rate, can be achieved by using DI and initiating combustion during fuel injection. This method enables the delivery of stoichiometric mixtures to ICEs, significantly increasing the heat produced by the engine without entering the abnormal combustion zone. This can enable high engine performance compared to engines running on lean mixtures. Filming and pressure recording in the isochoric chamber were used to study combustion, demonstrating the effectiveness of this approach for analyzing mixture formation and combustion.

2.5. Advanced injection strategies and emissions control

Using CFD modelling, Shi et al. [96] analyzed how different injection parameters – including the amount of H_2 per pulse, the inter-pulse interval, and the width of the minor injection pulse – affect engine efficiency and emissions. The results indicate that split DI enhances mixture stratification, resulting in faster and more efficient combustion than single injection. Increasing the mass fraction of post-injection and the interval between injections further improves combustion, as a longer minor injection pulse width enhances engine efficiency by enriching the mixture near the spark plug. However, while this approach reduces HC and CO emissions to nearly negligible levels, it increases NO_x emissions.

Shahpouri et al. [95] reported that to minimize NO_x and soot emissions from engines running on hydrogen, an engine can be enhanced with a hardware-in-the-loop (HIL) configuration, thereby reducing calibration work for the engine. Furthermore, optimal model-based combustion control (MCC) can lower engine-out emissions. Both HIL and MCC methods need rapid and precise models for NO_x and soot emissions. The precision of a rapid physics-based engine model utilizing premixed combustion relies on forecasting the laminar flame speed (LFS). The authors forecasted LFS using an artificial neural network (ANN) machine learning (ML) approach. The LFS model and the engine combustion model are validated for both an H_2 SI engine and an H_2-diesel CI engine. The black-box and gray-box models for soot and NO_x emissions were created for the H_2-diesel engine utilizing ANN, support vector machine (SVM), and Gaussian process regression (GPR) techniques with various feature sets, and are then compared to a standard one-dimensional physics-based NO_x model. The gray-box emission models were ideal for engine HIL configurations where precision is crucial. The black-box models were appropriate for model-based real-time control of H_2 combustion when computational power is restricted.

2.6. Syngas combustion and engine adaptation

Hagos et al. [39] analyzed the properties of three distinct syngases derived from major gasification products of low and medium calorific values, comparing them to CNG and H_2. Syngases, especially those with a medium calorific value, have an adiabatic flame temperature similar to that of H_2, resulting in increased NO_x emissions. Syngases have a much lower stoichiometric A/F ratio compared to CNG and H_2, which may increase brake specific fuel consumption (BSFC).

Fiore et al. [29] reported that syngas fuel serves as an intermediary phase in the transition from carbon-based to H_2-derived fuels. Syngas-powered dual-fuel engines achieve notable standard fuel savings. Syngas has low knocking propensity and allows the use of high compression ratios (CRs). Its broad flammability range favors lean combustion. Dual-fuel CI engines, homogeneous charge spark ignition engines, and DI SI engines are highly sensitive to the physical and chemical properties of syngas, such as CO and H_2 content, laminar flame speed, broad flammability range, and lower density compared to air. The authors also noted that large-eddy simulations or even direct numerical simulations should be conducted, and models require further improvement and validation. Models addressing turbulence-chemistry interaction should be tested, especially for high-speed DI of syngas. Multicomponent diffusion models should be included, as H_2 diffuses much faster than other mixture components. Intake and exhaust processes, typically neglected in syngas port-injection engine simulations, must be considered, as a significant part of power derating is linked to reduced volumetric efficiency. These processes must be included in high-fidelity data assessment.

Paykani et al. [78] examined the impact of syngas use on the performance and emissions of SI, CI, HCCI, and advanced dual-fuel engines like reactivity-controlled compression ignition (RCCI) engines. Many factors affecting both syngas and engine properties significantly influence the prospective benefits of syngas use in ICEs. Variations in the H_2 fraction of syngas have limited its broad application. Additional gaseous components, such as CO_2, N_2, and CH_4, in syngas may negatively impact engine combustion. The key reasons for power loss in SI engine are the low energy density of syngas/air blends and reduced volumetric efficiency due to air replacement. Adding high H_2-content syngas as a secondary fuel improved combustion and performance compared to low H_2-content syngas. Using high CRs in syngas-powered engines reduced power loss without increasing knocking. DI of syngas can also eliminate power derating, avoiding issues related to reduced volumetric efficiency and unintentional pre-ignition or surface ignition in the intake system.

2.7. Material issues: hydrogen embrittlement

As noted by [89], the intended replacement of conventional fuel in combustion engines with H_2 may cause hydrogen embrittlement, particularly in various steel-based materials, depending on material type, structure, and operating conditions. The authors described the process of electrochemical hydrogenation, similar to galvanic coating of metals used in the automotive industry. They assessed how hydrogenation duration affects the properties and microstructure of austenitic steel. They found that the material was strengthened by electrochemical hydrogenation in a 0.5M H_2SO_4 solution. The increase in strength was directly related to the amount of H_2 supplied. However, the typical features of hydrogen embrittlement, such as localized brittle fracture areas reported in the literature, were not observed in the analyzed material.

2.8. Summary and research directions

Several mechanisms describing H_2 combustion have been published recently, exhibiting varying degrees of complexity and accuracy.

Various out-of-engine studies on the effect of H_2 combustion have utilized CFD methods, investigating not only pure H_2 but also gases containing high H_2 content, such as syngases.

The application of combustion engines fuelled with H_2 and fuel cells (FCs) in vehicles is discussed in the following subchapters.

The use of the dual-fuel ICEs supplied with fuel and H_2 is presented in Part 2 of this review. It can be noticed that the efficiency of such ICEs can be enhanced, for example, by applying new solutions to their injection system, such as a hypocycloid mechanism in the drive of pumping sections of high-pressure pumps for diesel combustion engines and the others [9, 12, 64].

3. Combustion engines supplied with H_2

Escalante and Fernandez [27] stated that in ICEs fueled by H_2, the emissions from air/H_2 mixtures primarily consist of CO_2 and NO_x. For NO_x, higher emissions occur because H_2 combustion produces higher flame temperatures and flame speeds than other fuels, such as gasoline. Emissions of unburned hydrocarbons (UHC) result from the heating of lubricant oil and the use of oil-based coolants. The thermal efficiency of a H_2-fueled engine (38.9%) exceeds that of a gasoline engine (25%). The power output by a H_2-fueled test engine reached 80% of the output of a gasoline engine. At light loads, H2 combustion can minimize NO_x emissions and prevent abnormal combustion phenomena by shortening the injection duration and delaying the spark timing. Spark-ignition (SI) engines can operate efficiently with air-H_2 mixtures at equivalence ratios between 0.3 and 0.9, using compression ratios (CR) above 12:1, exhaust gas recirculation (EGR), shorter injection durations, and delayed spark timing. Nearly ideal functioning of compression-ignition (CI) engines requires increasing CR, using EGR, and primarily employing a combustion inducer (such as diesel) while adding an H_2 mixture to achieve the desired power output. Replacing hydrocarbons requires research on CI engines powered by H_2 and diesel, operating at CR above 15:1, using natural gas (NG) injectors, and variable

H_2 loads, starting from low loads until minimal HC levels are achieved, utilizing a combustion initiator.

From an engine design perspective, the primary modifications suggested for using H_2 as a fuel include:

- Replacement of injectors: Larger injection volume capacity is needed. The low density of H_2 necessitates rapid injection of larger fuel quantities. NG injectors can be modified to operate with H_2.
- Improved temperature management: The high combustion speed of H_2, compared to gasoline and diesel requires enhanced temperature control, such as cooling around nozzles, spark plugs, and cylinder heads.
- Mixtures: Using H_2 combustion alongside hydrocarbons is recommended as an initial phase of H_2 integration. Light blends with about 5–10% H_2 by volume can serve as a starting point for a gradual, clean transition from traditional fuels.

Verhelst et al. [120] stated that due to its physical and chemical characteristics, H_2 is primarily employed in SI applications and is regarded as a baseline. The power output of an H_2 ICE is lower than that of a gasoline engine due to H_2's low volumetric energy density. H_2 occupies more engine volume, reducing the possible air intake per cylinder. This negative effect is partly offset by the higher heating value and stoichiometric air-to-fuel ratio, but it may still lead to a 17% reduction in power output. Although port fuel injection (PFI) has lower theoretical performance than other mixing systems, it remains the only system used in demo cars due to its simplicity and injector availability.

The authors further explained that the wide flammability range of H_2 benefits load control strategy, enabling a 'qualitative' load control approach that eliminates the need for throttling and associated losses. In this case, the A/F ratio is raised to decrease performance at partial loads, which works similarly to a diesel engine. Running the ICE with very lean mixtures additionally helps reduce NO_x emissions. Reintroducing exhaust gases (EGR) to the inlet is another method to lower ~~the~~ performance at part-load operations without throttling. The presence of the inert exhaust gases also reduces the amount of air and fuel in the engine. H_2 enables stable ICE operation with higher EGR levels than gasoline due to its broader flammability range and faster flame speed. The maximum power per engine displacement can be increased by raising inlet pressure using supercharging or turbocharging, with turbocharging being preferred for efficiency. However, the reduced throttle response and lower exhaust energy with H_2 compared to traditional fuels create challenges for turbocharged H_2 ICEs. Control methods based on power density or ICE efficiency are typically integrated into lean-burn and stoichiometric strategies. At low loads, the ICE operates with varying air-to-fuel (A/F) ratios, yielding high efficiency and very low emissions. When a specific power requirement is exceeded, the operation shifts to throttled stoichiometric mode. The performance achieved by this load control approach was reflected in a single-cylinder ICE map at BMW, later scaled to 12 cylinders in a demo car [122]. The map showed optimal performance between 4 and 6 bar IMEP (indicated mean effective pressure) with an indicated thermal efficiency (ITE) of 42%. This maximum efficiency is paired with a large portion of the map showing ITE values above 38%. However, the maximum torque reached about 10.3 bar IMEP, indicating lower power density compared to similar gasoline ICEs, mainly due to low inlet charge density and combustion limitations.

The authors also noted that the broad flammability range, high flame speed, and low ignition energy of H_2 improve engine efficiency but can also cause unwanted combustion events. The most common is 'backfire' - premature ignition of the H_2-air mixture during the intake stroke, leading to combustion in the intake system and possible failure. Preventing early ignition requires eliminating ignition sources such as hot spark plug electrodes and exhaust valves, and modifying the ICE. Keeping ignitable mixtures away from ignition sources is another way to prevent backfire. In this case, variable valve timing and carefully managed injection timing are used to prevent backfire by introducing a cooling period with fresh air and minimizing H_2 during the initial intake phase [1, 60]. Pre-ignition can also occur when the inlet valves are closed and the charge is compressed, resulting in extremely high pressures and potential damage. Ultimately, self-ignition (knock) of the unburned mixture can occur, as in any SI ICE. In an H_2 ICE, knock is less likely than in gasoline engines, but its effects may be more severe due to the high burning speed of H_2 mixtures.

H_2 PFI has been applied in various demonstration vehicles, either modified from existing models or purpose-built for H_2. Modifications for H_2 operation focus on the fuel system (from storage to injection) and engine control unit programming. Quantum Tecstar converted over 30 vehicles for H_2, using the Toyota Prius hybrid as a base. Two compressed H_2 tanks replace the gasoline tank, preserving the vehicle's interior. The Prius engine is turbocharged to boost H_2 performance. The Quantum H_2 Prius offers similar drivability to the gasoline version, with a range of 100–130 km and compliance with SULEV II emissions standards [121].

Designing a dedicated H_2 vehicle required additional hardware considerations [125].

Shinde and Karunamurthy [97] observed that current PFI and DI H_2 ICEs provide favorable brake thermal efficiency compared to gasoline ICEs. H_2 properties are better suited for gasoline-type engines, but specific adjustments are needed to utilize H_2's potential fully. For DI, a late injection strategy is recommended for optimal combustion. Efficiency losses must be minimized. EGR increases ICE efficiency, and further dehumidifying EGR improves it; thus, arrangements for EGR dehumidification are suggested. Downsizing the engine increases efficiency but also raises NO_x emissions, requiring a balance between NO_x and efficiency. Research should focus on hybrid fueling systems combining DI and PFI to enhance efficiency and lower emissions.

H_2-fueled ICEs have demonstrated higher-brake thermal efficiency than those using fossil fuels. However, irregular combustion such as backfiring in H_2-injected engines, limits performance improvements due to H_2's low ignition energy and high flame speed. Volumetric efficiency drops significantly during backfire, and damage to intake and fuel injection systems can occur. Backfire is triggered by residual exhaust gas at high temperatures, hot spots, and irregular spark plug discharge, which promote pre-ignition of the H_2-air mixture. Gao et al. [32] analyzed factors leading to backfire, including incorrect valve and injection timing and high A/F ratios, and reviewed backfire control methods, discussing their pros and cons. The main causes are excessive residual exhaust gas, slow combustion, and uneven H_2 distribution near intake valve seats. Backfire control strategies require specific conditions to remain effective; outside these, they may negatively impact results. Power loss is almost unavoidable for naturally aspirated ICEs when backfire prevention is implemented. Various strategies are recommended to mitigate performance loss, and multi-objective optimization is proposed to achieve the best overall efficiency.

BMW created the H_2 7 car with a dual-fuel system that allows for operation on either H_2 or gasoline. In H_2 mode, it uses a variable A/F ratio lean-burn strategy for low and medium loads, and a throttled stoichiometric approach for high loads. Approximately 8 kg of H_2 are stored in a cryogenic tank in the trunk, providing a range of 200 km. Emission tests of a mono-fuel H_2 7 variant showed very low emissions. Using a special after-treatment system with two catalysts (one for stoichiometric and one for minimizing NO_x spikes during transitions), the car achieved drive-cycle NO_x emissions of 0.0008 g/mi, just 3.9% of the SULEV II threshold [43].

Vogel [124] developed a large diesel engine with H_2 DI into the combustion chamber, achieving high power density and reduced exhaust emissions. Combustion occurred via self-ignition, following the diesel principle, with H_2 as the energy source, allowing CO_2-free operation.

Prechtl and Dorer [83] reported that H_2's properties and use in high-power, large-displacement engines led to the concept of an engine with internal mixture formation and CI. A system developed by MAN B&W used electro-hydraulic control for injection. H_2 was injected at high pressure in gaseous form, with experiments and 3D flow simulations performed. The ignition process was modelled in 1D chemical simulations. Combustion in a diesel ICE is feasible, and the mixing system is key for effective H_2 combustion in large diesel ICEs.

Rottengruber et al. [88] performed studies on a DI H_2-powered diesel engine, injecting H_2 at high pressure near top dead center and igniting by self-ignition. This was systematically tested on a single-cylinder engine. Combustion was analyzed using custom software to generate pressure curves and engine mechanics, and a computational model was developed to predict NO_x emissions.

Some researchers have investigated various H_2-fueled engines (see Table 1).

Brzeżański and Rodak [15] conducted theoretical and experimental work on a Kipor 186F SI ICE modified for H_2. The engine utilized an H_2 DI system in the combustion chamber, enabling the regulation of heat release rate. H_2 DI, compared to inlet channel injection, greatly expanded the engine's operational range and prevented knocking. The right DI approach enabled combustion with a lower excess air coefficient, approaching stoichiometric conditions. This increased maximum cylinder pressure and improved engine parameters, with no resultant knocking. The DI approach, employed during both the compression and combustion phases, enables H_2 to replace hydrocarbon fuels in ICEs fully.

Brzeżański and Rodak [16] also analyzed NO_x formation during H_2-air combustion in an SI ICE. They developed a strategy for generating and combusting H_2-air mixtures, ensuring low NO_x. This approach limits the N and O_2 reaction during operation. Preliminary tests have shown that this injection strategy enables progress monitoring. Unlike previous H_2 supply systems, this method allowed stoichiometric combustion without anomalies or auto-ignition. Monitoring the heat release rate and in-cylinder pressure rise was also possible. These engine parameters strongly influenced burning characteristics and NO_x emissions. The developed system avoided knocking and allowed full NO_x emission monitoring. Burning progress and NO_x propensity can be evaluated by average pressure rise. Tests over a wide H_2-air mixture range (λ = 2.03–1.05) showed that NO_x generation depends more on temporary pressure rise (and thus temperature) than O_2 availability. The H_2 injection strategy, which allows injection during either the compression or both compression and combustion phases, depending on the operating point, significantly influences operating parameters and NO_x emissions, and could inform regulatory guidance.

Szlachetka et al. [109] simulated a gaseous fuel delivery system in a Wankel engine using a zero-dimensional model of the injector set, with gaseous H_2 injected into the RX 50 Wankel engine's intake manifold. The study was conducted at 3700 rpm and an inlet pressure of 0.4 MPa. Pressure time profiles in the fuel pipe and injector-to-intake tubing were analyzed. Maximum pressure fluctuations in the fuel rail reached 0.016 MPa at injector closure. Notable changes in fuel flow in the pipe to the intake manifold were observed, up to 0.002 kg/s. The maximum average injector mass flow was 0.00325 kg/s.

Mitianiec [69] noted that Wankel engines may be attractive in automotive applications due to their small size, compactness, simple design, smooth operation, and reduced vibration resulting from inertia forces. The main drawback is significant pollution (HCs, CO) and high BSFC, which can be addressed by H_2 DI and, in aviation, by using high-octane fuel in DI systems. The researcher simulated thermodynamic processes during scavenging, utilizing engine geometry, initial and boundary conditions to compute pressure, temperature, density, heat exchange, and volume as a function of piston angle in a zero-dimensional model. Mixture formation during compression-phase injection provided insights into air excess ratio. The model can be used for various fuels. Using H_2 lowers emissions but also reduces efficiency.

The author concluded that:

1. While the inlet port is opened, only a brief moment is available to fill the chamber with fresh air. Emission discharge continues longer due to high pressure, depending on the outlet port area. Rotor contact points should be minimized for effective sealing.

2. For naturally aspirated rotary Wankel engines, volumetric efficiency remains below 1.0 due to emissions that hinder air flow into the chamber.
3. Fuel injection must occur during the compression phase to minimize fuel waste.
4. A gasoline-homogeneous mixture engine produces more internal work (and power) than an H_2 engine, due to gasoline's higher caloric value under the same settings.
5. The mass of charge in the naturally aspirated Wankel engine varies slightly with engine speeds.
6. Exhaust pressure within in the port is largely unaffected by the fuel at the speed.
7. The engine achieves peak power at high speeds, specifically 12,000 rpm in this case.
8. To achieve high overall efficiency, a DI fuel layout is needed for stratified charge.
9. The scavenging process is crucial for ported engines.

Szwaja [110] studied knocking in an H_2-powered engine. Knocking intensity was defined as in-cylinder pressure fluctuations (sampled at 100 kHz) and processed with high-pass filtering (cutoff at 3.5 kHz). The study used a CFR engine with variable CR (6–14). A sharp rise in pressure pulsation amplitude was observed as CR rose from 11 to 12, attributed to auto-ignition of the H_2-air mixture at the end of SI-controlled combustion. The dual nature of H_2 knock combustion was proposed. Pressure pulsation intensity during regular combustion (without H_2 auto-ignition) showed an exponential relationship with CR, directly related to the temperature of the H_2-air mixture at ignition.

Kovar et al. [55] evaluated H_2-fueled engines, focusing on mixture formation, combustion of air-H_2 mixtures with varying A/F ratios, NO_x emissions, and power characteristics. Studies were conducted on a single-cylinder test engine (naturally aspirated and supercharged) and a six-cylinder turbocharged engine. Main technical challenges in H_2 engine development are (i) reduced power due to lower volumetric energy density of H_2/air mixtures, and (ii) issues like backfire and early ignition. Engine concepts like turbocharging, intercooling, and internal blending with A/F equivalence ratio $\Phi < 0.5$ can increase efficiency while keeping NO_x low. The safest H_2-powered engine system utilizes an in-cylinder fuel mixer, where air is drawn in first, followed by H_2 DI into the cylinder. No backfire was observed in lab tests (even when H_2 was introduced before inlet valve closure at ~1 MPa).

Szwajca et al. [111] examined a two-stage passive H_2 combustion setup for knock studies under various conditions. Experiments with a single-cylinder AVL 5804 engine assessed the effect of center of combustion (CoC) and excess A/F ratio (λ) on knocking and its metrics. Tests at 1500 rpm, with CoC (2–18°CA aTDC) and $\lambda = 1.25$–2.0, showed strong knock at $\lambda = 1.25$–1.5, requiring higher λ to suppress it. Knocking depended more on λ than on CoC.

Lee et al. [57] studied H_2 DI, assessing three mixing methods: homogeneous, lean homogeneous, and lean-stratified in a single-cylinder ICE. Results show that H_2's significant heat loss requires delaying combustion. The lean-stratified charge (LSC) mode, designed to reduce high-temperature zones near the cylinder wall, achieved the highest BTE (34.09%) at low loads. However, this also increased NO_x emissions, illustrating the trade-off between efficiency and emissions in H_2 DI systems.

Bao et al. [11] tested a 2.0L turbocharged H_2 DI ICE, achieving 120 kW at 4400 rpm and 340 N·m at 2000 rpm. Peak BTE was 42.6% with a mildly lean A/F ratio (λ = 1.91) at 2000 rpm. NO_x emissions dropped by over 99.5% at speeds below 2000 rpm and by about 90% at 4400 rpm, with two-thirds of cases achieving NO_x below 20 ppm using an NH_3-SCR after-treatment system. This confirms that H_2 DI ICEs can deliver high power, efficiency, and near-zero emissions.

Wróbel et al. [132] reviewed advances in H_2 combustion vehicle technology, highlighting prototypes and summarizing key features (see Table 2). Since H_2 engine drivelines are mechanically similar to conventional ones, they are ideal for operators in challenging environments or those seeking stable maintenance costs. H_2 engine development is promising for applications that do not require dense refueling infrastructure. H_2 combustion vehicles tolerate varying H_2 quality, operate in harsh conditions, are reliable and user-friendly, and are mature, tested technology that ensures independence from rare earth metals. The main drawback is NO_x emissions, requiring exhaust treatment.

According to [87], just a year after its prototype was revealed in October 2021, HYVIA presented the H_2-powered Renault Master Van H2-TECH at the Paris Motor Show 2022. Its main advantages are zero emissions, a 5-minute refueling time, and a 400 km range. The Master Van H2-TECH is a spacious van with 12 m^3 cargo capacity, a 30 kW FC, a 33 kWh battery, and tanks for 6.4 kg of H_2.

Various strategies are employed to enhance H2 combustion and ICE efficiency while minimizing harmful emissions, including optimized A/F ratios, sophisticated injection systems, and EGR. These methods aim to enhance combustion efficiency, reduce NOx emissions, and minimize the production of other pollutants [34, 77, 104].

Optimized combustion can be realized via:

- Control of the air-fuel mixture is essential, as accurate management of this ratio is crucial. Operating the engine in a "fuel-lean" mode (with surplus air) can enhance efficiency. The rapid flame speed of H_2 enables stable combustion, even under lean conditions [6, 31, 50, 70, 84, 133].
- Injection techniques, particularly high-pressure DI systems, provide enhanced control over the timing of combustion and fuel distribution, resulting in improved efficiency and performance [34, 99].
- Stratified combustion, which employs stratified or spark-assisted diffusive combustion, can enhance combustion features and improve thermal efficiency [34].
- The timing of ignition, as sophisticated ignition systems can be employed to enhance the timing of combustion, ensures it occurs at the most efficient moment within the engine cycle [7, 34, 137].

Emission control can be realized via:

- EGR lowers combustion temperatures, which aids in reducing the creation of NO_x [3, 34, 50, 77],.
- Catalytic converters, because although hydrogen burning mainly generates water. Catalytic converters can also minimize NO_x emissions [34, 104, 113, 117].

Table 1. Selected combustion engines supplied with H_2

Refs	Type of engine	Combustion system	Bore × stroke [mm]	Displacement [dm^3]	CR [-]	Power output [kW]/speed [rpm]
[15, 16]	Kipor 186F, Single-cylinder, vertical 4-stroke, forced air cooled diesel	Single-cylinder, vertical 4-stroke, forced air cooled diesel. DI system. Modified by Heron chamber in the piston for a strong swirl during compression.	86 × 70	0.406	Original 19.3, after modification of burning space 15.1	Continuous 6.6, Maximum 7.4/3600
[110]	CFR Waukesha Single cylinder SI 4- 4-stroke water cooling		8.26 × 11.43	0.611	4.5–18.5	
[55]	OKC-Octane Single cylinder SI 4-stroke both naturally aspirated and supercharged	gas DI		0.61	8:1	
[55]	LIAZ ML637ENE 6-cylinder SI 4-stroke turbocharged		130 × 150	11.946	12:1	160/2000
[111]	AVL 5804 1-cyl., 4-valve, SI, TJI, supercharged	H_2 supplied from cylinder to main chamber at 6.5 bar. Two tanks in series before injector to reduce pressure pulsation.	85 × 90	0.5107	14.5:1	
[57]	Single-cylinder SG–DISI	Highly pressurized H_2 injected from three cylindrical vessels via modified piezo-actuated gasoline injector, with fire arrester and H_2 detector.	85 × 88			
[11]	4-stroke, DI H_2-fueled			1		

Table 2. Selected prototype cars with H_2-fuelled ICEs (based on [132])

Model	Engine	H_2 Tank	Range (km)
Ford P2000 (2001)	ICE 2.0 l straight-four engine Zetec (port injection)	Compressed (87 dm^3, 250 bar, 1.5 kg)	100
Ford Shuttle Bus (2004)	ICE 6.8 l V10 Triton	Compressed (350 bar, 29.6 kg) *	240–320
ETEC Chevrolet Silverado (2004)	ICE 6.0 l V8	Compressed (3 × 150 dm^3, 350 bar, 10.5 kg) *	230–260
Toyota Quantum Prius (2005)	ICE 1.4 l straight-four engine (electronic multi point H_2 injection)	Compressed (1.6 kg)	100–130
Toyota Corolla (racing vehicle) (2021)	ICE 1.6 l 3-cylinder turbo with intercooler	Compressed	
Lexus RC F designed vehicle (2022)	ICE 5.0 l V8		

* Note: The higher brake specific fuel consumption BSFC is due to the relatively larger size and ~~car~~ weight of these vehicles.

- Lean burn approaches, which involve operating the engine in a lean manner, enhance efficiency and decrease the release of specific emissions [4, 26].

  Modifications to the engine can be focused on [7, 77, 85]:
- Material enhancements, as the combustion of H_2 can be detrimental to engine parts. Changes such as reinforced valves and seats, upgraded connecting rods, and altered inlet manifolds are frequently required.
- Elevated voltage ignition, as H_2 needs a more powerful spark to ignite. Therefore, ignition coils with higher voltage might be needed.
- The injectors' design, as they are meant for gaseous fuels, is essential for the efficient delivery of H_2.

  Additional considerations specific to H_2 include [33, 62, 104, 108, 112]:
- Lubrication plays a crucial role in engines supplied with H_2, as the low lubricity of H_2 can create difficulties. A careful choice of lubricating oils, along with possibly other additives, may be necessary.
- Combustion instabilities, as in H_2 burning, may be susceptible to them. Sophisticated control methods are necessary to ensure consistent and reliable performance.
- H_2 embrittlement, as H_2 may induce it in specific metals. The selection of materials and the design of the engine need to consider this.

  Improvements in performance can be reached via:
- Turbocharging and supercharging, which can enhance the volume of air drawn into the ICE, boosting power production [23, 34, 99, 135].
- Dual-fuel operation realized by combining H_2 with fuels, like NG to rise efficiency and lower emissions [10, 99].
- Incorporation of nanomaterials into H_2 to enhance thermal conductivity and heat transfer [81].

4. Vehicles with fuel cells (FCs)

Pramuanjaroenkij and Kakaç [82] reported that H_2 can be supplied to fuel cells (FCs) to generate electricity for powering vehicles, resulting in zero greenhouse gas emissions and requiring no direct combustion.

FCs serve as energy-conservation technologies for the 21st century, applicable to mobile, stationary, and especially FC electric vehicles (FCEVs), which are classified as zero-emission vehicles. H_2 FC vehicles, which use hydrogen as a power source, are also referred to as hydrogen electric vehicles or FC electric vehicles. Many individuals mistakenly thought that FCs were batteries; however, FCs can continuously generate electric power as long as they receive a constant fuel supply. Batteries can supply electrical energy only as long as their stored charge permits; once depleted, they provide no further energy. FCs have been utilized in various applications, including unmanned aerial vehicles (UAVs), unmanned underwater vehicles (UUVs), as well as automobiles, trucks, and buses. Over the past five years, research on FCs has focused on catalysts and membranes, fluid flow fields, motors and converters in FC vehicles, sensors and controls, cooling methods for FCs, machine learning applications, modeling, simulations of FC vehicles, and especially energy management systems within these vehicles.

As noted in [41], the path to widespread acceptance of hydrogen fuel cell vehicles (HFCVs) is fraught with challenges. Central to these issues are the substantial costs associated with vehicle manufacturing and H_2 FC technology, insufficient refueling infrastructure, and concerns regarding the efficiency and environmental impact of H_2 generation. Despite these challenges, technological advancements, economies of scale, and significant investments in research and development (R&D) could help overcome these barriers.

Stakeholder involvement is essential for advancing HFCVs. Car manufacturers such as Toyota, Hyundai, Honda, and Mercedes-Benz are continuously improving their HFCV models, demonstrating strong commitment to this technology. However, a broader transition to HFCVs requires a more comprehensive set of actions and collaborations, including public education initiatives, development of H_2 infrastructure, and funding for research to improve the cost and efficiency of HFCVs.

Government initiatives and policies also play a significant role in the adoption of HFCVs. Governments can promote the development of HFCVs through financial incentives, infrastructure development, clear regulations and standards, and public awareness campaigns. Governments must integrate HFCVs into their broader energy, environment, and economic strategies to ensure balance and consistency. The advancement of HFCVs is closely linked to the broader expansion of the hydrogen economy.

Fang et al. [28] evaluated the current status of fuel-cell electric vehicles (FC-EVs), ongoing research, and the associated challenges and opportunities. Proton-exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs) face significant obstacles to widespread adoption. PEMFC vehicles are challenged mainly by high costs, limited durability, and infrastructure gaps. The reliance on expensive platinum-based catalysts increases production costs, while degradation from catalyst poisoning and membrane failure affects long-term viability. Additionally, the lack of H_2 refueling stations is a significant barrier to the adoption of PEMFC vehicles.

In contrast, SOFCs do not require costly platinum group catalysts; however, SOFC vehicles face challenges related to high operating temperatures, fuel flexibility, system complexity, and stack degradation. Operating at 500–1000°C, SOFCs encounter issues with thermal management and material compatibility. Ensuring efficient operation with various fuel types, optimizing system design, and minimizing stack degradation are crucial for advancing SOFC technology. Collaborative R&D efforts are crucial for addressing these challenges and accelerating the adoption of both PEMFC and SOFC vehicles as sustainable transportation solutions.

Günaydın et al. [37] compared passenger and commercial H_2 FC vehicles with internal combustion engine (ICE) cars, plug-in hybrid electric vehicles, and battery electric vehicles, focusing on well-to-wheel efficiency, range, fuel consumption, refueling/recharging time, emissions, and vehicle costs. They found that while battery electric vehicles (BEVs) lead the passenger vehicle market due to lower costs and expanding infrastructure, HFCVs are well-suited for commercial vehicles, offering fast refueling and long range. The transition to HFCVs faces hurdles, including limited infrastructure compared to gasoline and electric systems, as well as the higher cost of hydrogen production relative to gasoline and electricity, both of which must be addressed for widespread adoption. The increasing use of renewable energy may reduce electricity costs for electrolysis, thereby lowering overall hydrogen production costs and facilitating the generation of green hydrogen. Recent years have seen significant growth in hydrogen infrastructure and electrolysis capacity worldwide, particularly in Asia-Pacific countries. Enhanced government incentives and investments, along with financial support for consumers and manufacturers, are vital for increasing HFCV adoption. Additionally, R&D efforts are crucial for advancing hydrogen infrastructure and production technologies.

Baba et al. [8] examined the use of FCs and energy management in hybrid vehicles. FC vehicles offer significant advantages over battery-electric vehicles in terms of range, energy efficiency, charging time, and adaptability to different climates. The classification and a brief overview of HEVs/FCs are provided, followed by a summary of FC HEVs that illustrate various hybrid vehicle configurations.

Topological categorization

Hybridization refers to the integration of two energy sources and one propulsion type, or two types of propulsion. In HEVs, this means combining electric and thermal propulsion. In FCEVs, the system starts with the battery supplying energy to the DC bus [63]. The DCU maintains steady bus voltage and delivers propulsion energy to the motor drive converter. The DC/AC converter controls motor speed and torque, and the motors convert electrical energy into kinetic energy [80].

1) Complete FCEV framework: The FC stack serves as the sole energy source, comprising a DC-DC converter, fuel tank, FC stack, inverter, and electric motor [40], which provides high efficiency, a simple design, system reliability, and a user-friendly driving experience [40].
2) FC + Battery integration: This design includes a unidirectional DC-DC converter (UDC) connected to the storage system and an inverter directly linked to the motor. The storage system provides the high current needed for engine startup [40, 91].
3) FC + Ultracapacitor (UC) hybridization: This configuration utilizes an ultracapacitor to extend the life of the storage system, but its low energy density limits its application to short-term use [90].

4) FC + (Battery + UC) hybridization: This setup includes an FC connected to the DC bus, with two DC-DC converters (one unidirectional and one bidirectional) located between the FC and the capacitor [80, 90].
5) FC + battery + PV hybridization: A hybrid system combining FC, battery, and photovoltaic (PV) sources, with the storage system linked to the DC bus via a bidirectional converter. PV power depends on solar radiation and temperature [73].

Such topologies were presented in Fig. 1.

According to Voelckner [123], since 2015, three H_2-fueled vehicles have been available for purchase from major automakers: the Honda Clarity FC, Hyundai Nexo SUV, and Toyota Mirai. However, Honda has discontinued all Clarity models. Hyundai has sold only about 1600 Nexo SUVs in six years, and Toyota has sold approximately 14,300 Mirai sedans in the U.S. over two generations, sometimes relying on substantial discounts to boost sales. In 2025, Honda will launch the CR-Ve: FCEV, an improved compact crossover with a hydrogen FC (co-developed with GM) and a larger battery for plug-in charging, offering 29 miles of electric range and 241 miles from the FC. It will be available for lease in California only, with an expected annual volume of 300 vehicles.

According to [127], there are two main types of pure electric vehicles using FCs as their primary electricity source: FC electric vehicles (FCEVs) and FC hybrid electric vehicles (FCHEVs). The primary challenges in FC electric mobility include low FC efficiency, cold start issues, difficulties with hydrogen storage, the need for cost reduction, safety risks, and traction system problems.

Waseem et al. [128] noted that energy storage for electric vehicles can be achieved using various technologies, including lithium-ion batteries (LIBs), lead-acid batteries (LABs), solid-state batteries (SSBs), FCs, and ultracapacitors (UCs).

Samuel et al. [92] analyzed a hydrogen FC vehicle based on the Toyota Mirai and confirmed its fuel efficiency using real-world test data. This validated model was used to calculate fuel efficiency for actual driving cycles recorded in Mexico City in 2019, encompassing three distinct drive cycles that accurately reflect real urban driving conditions.

On February 28, 2024, at the 16th Expo Foro Movilidad in Mexico, FOTON unveiled the HC12 hydrogen fuel cell bus, the first hydrogen FC bus in Mexico. The HC12 features a 120 kW fuel cell engine and a 35 MPa hydrogen system, offering a range of up to 550 km (400 km from hydrogen, 150 km from electricity). It is emission-free, environmentally adaptable, highly safe, and fuel-efficient, making it ideal for medium- to long-distance transport, luxury tourism, and group services [30].

Thanks to hydrogen technology and larger, lightweight hydrogen tanks totaling 51.2 kg, the Solaris Urbino 18 H_2 bus excels on long routes. The BALLARD FCmove HD+ FCs, rated at 100 kW, achieve 57% efficiency and can operate for over 30,000 hours between –25°C and +50°C. The bus is powered by a 240 kW motor, delivering 1470 Nm of continuous torque and 2100 Nm peak torque [100]. Such buses have been tested in Brasov, Romania, and can be refueled in 5–10 minutes, offering a range of around 350 km. The cost is approximately EUR 700,000, which is about EUR 100,000 more than the electric model. The Solaris hydrogen bus has also been tested in Cluj-Napoca and Târgu Mureș [46].

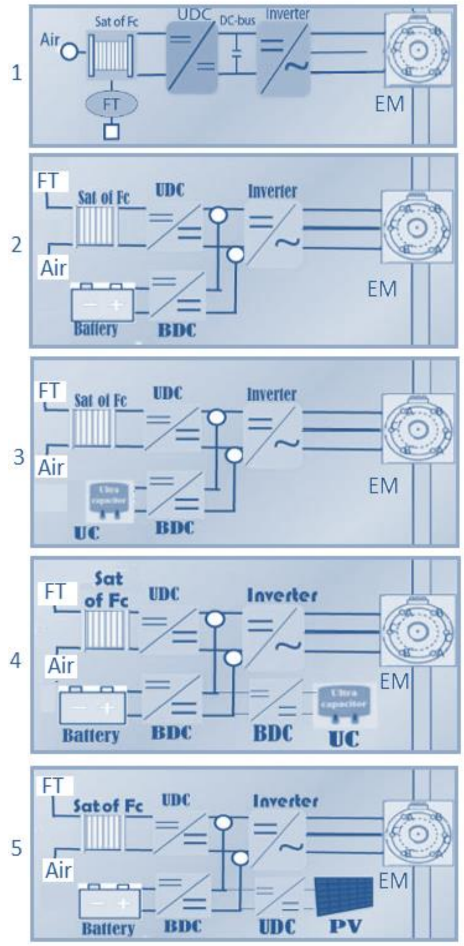

Fig. 1. Topologies of vehicles with fuel cells (FCs): 1 – The complete FCEV framework, 2 – The FC design + Battery integration, 3 – The FC arrangement + UC hybridization, 4 – The FC + (Battery + UC hybridization) set, 5 – The FC arrangement + Battery + PV hybridization arrangement

Currently, two major technical challenges for H_2 FCs are the high cost of catalysts and the frequent replacement of membrane materials that do not meet durability requirements [136]. According to [20], dynamic loading and FC costs are the main barriers to the successful commercialization of FCEVs and FCHEVs.

Issues related to hydrogen transportation can be addressed with innovative storage materials that are lightweight, strong, cost-effective, and suitable for long-distance, high-capacity delivery. For example, Zhang Jinying's team at Xi'an Jiaotong University utilized graphene for hydrogen storage, addressing challenges related to storage and transport. By using NaH or LiH as raw materials and controlling the encapsulation area of graphene, they achieved stable hydrogen release via interfacial nanovalve control [56]. Using NaH or LiH as fuel allows for higher hydrogen storage density and is suitable for other gases as well. These materials offer strong chemical stability and mechanical strength, making them suitable for high-temperature applications and emergency power for vehicles, drones, and semi-mobile devices [56].

Proton exchange membranes are essential for all types of H_2 FCs, but are very expensive. The widely used RSO_3H (R = organic group) Nafion membrane, produced by DuPont, has a high cost and limited ion transport, which raises the price of H_2 FC vehicles. The catalysts used are also extremely expensive, costing twice as much as gold, further limiting the advancement of H_2 FCs [136].

Brzeżański et al. [17] conducted initial tests, approximately 2.5 hours in duration, on the Toyota Mirai FC powertrain in a thermoclimatic chamber at temperatures ranging from –10°C to –18°C, simulating winter conditions in temperate climates. They found that the operating principles and methods of the FC power unit differ significantly from those of combustion engines. Since climate conditions greatly affect FC performance, testing in a thermoclimatic chamber was necessary. During the tests, the drive system and electrical components were covered with condensed water, but no operational disruptions were observed.

Pielecha et al. [79] examined a Toyota Mirai model with a FC hybrid system (see Table 3), which shares many design features with hybrid cars. Innovative FC technologies were implemented, including compressed hydrogen tanks and advanced control systems. The study analyzed FC operation during ignition and driving, focusing on the hydrogen injection method of the three fuel injectors. The relationship between the FC and the high-voltage battery was also examined. It was demonstrated that increasing the electric motor's supply voltage at high torque levels results in a threefold voltage gain (up to approximately 650 V), doubling the drive system's torque compared to standard values.

Table 3. Toyota Mirai vehicle drive system characteristics [115]

Parameter		Value
Vehicle	mass	1850 kg
	maximum speed	179 km/h
Vehicle range	type approval cycle	approx. 550 km (NEDC test)
FC	type	PEM (polymer electrolyte)
	power	114 kW
	power density	2.0 kW/kg; 3.1 kW/dm^3
	cell number	370
	humidification	internal circulation
Electric motor	type	synchronous AC
	maximum power	113 kW
	maximum torque	335 N·m
Battery	type	NiMH
H_2 storage	volume of tanks pressure/mass	front – 60 dm^3, back – 62.4 dm^3 70 MPa/5 kg H_2
Refueling	time	3 min

Małek [61] reported that the method of supplying fuel to the FC cathode significantly affects the durability and efficiency of hydrogen energy conversion. FCs are inherently variable systems. The researchers studied a Nexa FC module (1.2 kW net output). To control the pump's airflow, a master-slave regulator was designed, featuring a sub-regulator that works in conjunction with a brushless motor speed controller to adjust the airflow. A separate brushless motor was connected to the main regulator output. This approach allowed testing of different airflow regulation techniques independently of the initial controller's protocols. Airflow regulation of the PEM FC enabled identification and maintenance of the peak net power output of the FC stack, regardless of variations in controlled object parameters and external conditions. Adaptive extremum control with bi-factor assessment enabled automatic adjustment of controller parameters in response to changing system characteristics, improving both the value and speed of finding the optimum operating point.

While the development and market introduction of FC electric vehicles are progressing rapidly, several challenges remain for their practical application in vehicles, limiting the widespread adoption of FC technology in automotive powertrains. The main issues are [101]:
– Limited flexibility in power flow control in PEMFC + battery systems
– Significant power flow losses in PEMFC + battery + ultracapacitor configurations, complicating energy management
– Low battery power density results in larger, more expensive battery systems and increased vehicle mass.

5. Summary

Several mechanisms describing H_2 combustion have been developed recently, exhibiting varying degrees of complexity and accuracy. Further studies are needed to facilitate the incorporation of such mechanisms into AI-based modeling of H_2 combustion and control algorithms for real applications, including internal combustion engines (ICEs).

Future research might focus on increasing H_2 production from renewable sources, investigating novel materials or production techniques that reduce the costs of fuel cells (FCs) and H_2 generation, improving storage and distribution methods, and advancing materials science to lower FC costs. Additionally, it is crucial to perform a life-cycle assessment of hydrogen fuel cell vehicles (HFCVs), especially focusing on the recycling or disposal of proton exchange membrane (PEM) materials, the long-term environmental benefits and trade-offs, and the potential for partnerships among governments, industry stakeholders, and academia to address ongoing technical and economic challenges.

The growth of the market for H_2 internal combustion engine (H_2ICE) vehicles heavily depends on advancements in H_2 infrastructure and the establishment of appropriate legal regulations. Further studies are needed for H_2 engines, particularly focusing on the development of exhaust gas treatment technologies to reduce NO_x emissions.

Fuel cell vehicles (FCVs) can reduce emissions and provide a clean energy alternative to gasoline-powered cars. However, their development depends on the availability of H_2 fuel and the expansion of refueling infrastructure.

Nomenclature

A/F air-fuel
BSFC brake specific fuel consumption
CI compression ignition
CNG compressed natural gas
CR compression ratio
DI direct injection
FC fuel cell
FI fuel injection
HEV hybrid electric vehicle
ICE internal combustion engine
NG natural gas
PFI port fuel injection
SI spark ignition

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Mariusz J. Nieścioruk, MEng. – mjniescioruk AEI, Poland.
e-mail: *mariusz.j@niescioruk.eu*

Prof. Andrei-Alexandru Boroiu, DSc., DEng. – Faculty of Mechanics and Technology, National University of Science and Technology, Politehnica Bucharest, Romania.
e-mail: *andrei.boroiu@upb.ro*

Prof. Gustavo Ozuna – Department of Industrial Engineering and Systems, Hermosillo 83000, University of Sonora, Mexico.
e-mail: *gozuna@industrial.uson.mx*

Prof. Agustín Brau Ávila, DSc., DEng. – Department of Industrial Engineering and Systems, Hermosillo 83000, University of Sonora, Mexico.
e-mail: *agustin.brau@unison.mx*

Przemyslaw Kubiak, DSc., DEng. – Institute of Vehicles and Construction Machinery Engineering, Warsaw University of Technology, Poland.
e-mail: przemyslaw.kubiak@pw.edu.pl

Marek Wozniak, DEng. – Department of Vehicles and Fundamentals of Machine Design, Lodz University of Technology, Poland.
e-mail: *marek.wozniak.1@p.lodz.pl*

Krzysztof Siczek, DSc., DEng. – Department of Vehicles and Fundamentals of Machine Design, Lodz University of Technology, Poland.
e-mail: *ks670907@p.lodz.pl*