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Review

Hydrogen Internal Combustion Engine Vehicles: A Review

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Abstract: Motor vehicles are the backbone of global transport. In recent years, due to the rising costs of fossil fuels and increasing concerns about their negative impact on the natural environment, the development of low-emission power supply systems for vehicles has been observed. In order to create a stable and safe global transport system, an important issue seems to be the diversification of propulsion systems for vehicles, which can be achieved through the simultaneous development of conventional internal combustion vehicles, electric vehicles (both battery and fuel cell powered) as well as combustion hydrogen-powered vehicles. This publication presents an overview of commercial vehicles (available on the market) powered by internal combustion hydrogen engines. The work focuses on presenting the development of technology from the point of view of introducing ready-made hydrogen-powered vehicles to the market or technical solutions enabling the use of hydrogen mixtures in internal combustion engines. The study covers the history of the technology, dedicated hydrogen and bi-fuel vehicles, and vehicles with an engine powered by a mixture of conventional fuels and hydrogen. It presents basic technology parameters and solutions introduced by leading vehicle manufacturers in the vehicle market.

Keywords: hydrogen internal combustion engine; commercialized hydrogen vehicle; hydrogen

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Citation: Wróbel, K.; Wróbel, J.; Tokarz, W.; Lach, J.; Podsadni, K.; Czerwiński, A. Hydrogen Internal Combustion Engine Vehicles: A Review. *Energies* **2022**, *15*, 8937. https://doi.org/10.3390/en15238937

Academic Editor: Andrzej Teodorczyk

Received: 10 October 2022
Accepted: 22 November 2022
Published: 25 November 2022

1. Introduction

Currently, the transport sector is heavily dependent on fossil fuels, leading to major contributions to emissions of carbon dioxide and pollutants. In the face of increasing environmental pollution and at the same time the rising demand for energy, the so-called "hydrogen economy" is one of the most promising pathways for the development of sustainable energy [1–4].

Hydrogen internal combustion engines are an important technology in the accelerated path to decarbonization. The beginnings of the technology date back to the 19th century, and intensive development took place in the early years of the 21st century. Since about 2010, a decline in interest in this technology has been observed, mainly due to the entry into the market of electric vehicles (powered by batteries), widely recognized as "zero-emission" solutions. However, taking into account the production process of batteries requiring the use of rare and sometimes toxic raw materials and problems with recycling, the use of electric vehicles on a large scale places a heavy burden on the natural environment, and their zero emission status is highly questionable. Battery technology is perfect for passenger cars and selected utility vehicles. Meanwhile, the transport sector includes vehicles with a diverse set of work cycles and uses. Some of these vehicles and devices are currently not prioritized for applications in electric battery technology, which indicates that hydrogen technology could be a promising zero-emission solution for many utility vehicle operators.

A hydrogen-based energy system is regarded as a viable option for delivering energy service in an efficient, clean and safe manner while meeting sustainability goals [1–23]. Hydrogen can be produced from carbon-free resources or from fossil fuels combined with carbon separation and sequestration. The basic methods of obtaining hydrogen are: steam reforming of methane, partial oxidation of hydrocarbons, gasification of biomass, coal and wastes, thermal cracking, and electrolysis [1,3,5]. Most of those methods, except electrolysis and thermal cracking, produce carbon dioxide as a greenhouse gas, increasing he footprint of obtained hydrogen. Hydrogen is produced mostly for industrial purposes such as petrochemical hydrodesulfurization and hydrogenation, ammonia production and metal refining. Due to well-established production methods and the wide availability of substrates, hydrogen appeared as a possible carrier of energy and has been recognized as a fuel with some highly desirable properties for application as a fuel in vehicles, such as high gravimetric energy density. This approach needs to make hydrogen production more eco-friendly. Contemporary development utilizing renewable sources such as solar energy, wind power and geothermal energy may produce more energy than is required. The excess of energy can be stored in batteries, transferred to the common electricity grid or used for hydrogen production. Hydrogen becomes a carrier of energy, which can be stored as a compressed gas, liquid or as a metal hydride. Then, it can be utilized on-site or stored for later use or transferred to different locations. These make hydrogen easily obtainable without having access to fossil fuels and industrial-scale equipment [2,3,6,7].

The increased availability of hydrogen is an opportunity to develop new solutions, which undoubtedly include vehicles powered by hydrogen. There are two types of hydrogen vehicles: hydrogen combustion vehicles with a hydrogen-fueled internal combustion engine (ICE) and hydrogen fuel-cell vehicles with an electric motor powered by a hydrogen fuel cell (FC). Both hydrogen combustion engines and fuel cells use hydrogen fuel; however, hydrogen engines can run with hydrogen of lower purity. This is especially useful in the transportation industry, where the transition to high-quality green hydrogen will take time. Hydrogen engines are built on the well-known technology of internal combustion engines, which is of great benefit to vehicle manufacturers in the design and production of vehicles. This review is an attempt to deal with the subject of hydrogen-powered vehicles, with an emphasis on commercial vehicles. This publication is not a typical scientific monograph on vehicles with hydrogen internal combustion engines; it is a popular scientific approach to this problem. The study includes an overview of commercial vehicles powered by hydrogen internal combustion engines and solutions for the use of fuel blends with hydrogen.

2. Hydrogen Internal Combustion Vehicles Compared to Other, Similar Vehicles

In recent years, fuel cell vehicles have become more popular; nevertheless, hydrogen internal combust engine vehicles present much of the same promise as hydrogen fuel cell vehicles, i.e., high efficiency of the propulsion system and low air pollution emissions [3,8]. Both types of hydrogen vehicles (ICE and FC) have many advantages compared to typical gasoline vehicles (Table 1), which give them great opportunities for development.

Table 1. Comparison of the basic parameters of conventional gasoline vehicles, hydrogen combustion vehicles and vehicles powered by hydrogen fuel cells [8–22].

	Gasoline Vehicles	Hydrogen Combustion Vehicles	Hydrogen Fuel Cell Vehicles
Engine type	internal combustion engine	internal combustion engine	electric motor
Efficiency of the propulsion system	~30–35%	~40–50%	~45–55%
Fuel consumption *	approx. 9 L (or 12.8 kg) of gasoline/100 km	approx. 1.4 kg of hydrogen/100 km	approx. 1.0 kg of hydrogen/100 km

Table 1. *Cont.*

	Gasoline Vehicles	Hydrogen Combustion Vehicles	Hydrogen Fuel Cell Vehicles
Cost of fuel **	currently low (~0.1)	currently high (~0.9)	currently very high (1.0)
Air pollution emissions	high CO_2, CO, unburned hydrocarbons, and NO_x emissions	minimal/very low CO_2 and CO emissions, the same or up to 20% higher NO_x emissions compared to gasoline vehicles	minimal/zero CO_2 and NO_x emissions
State of technology	developed (widely used all over the world)	developed, and in diffusion stage (experimental vehicle series)	developed, and in diffusion stage (experimental vehicle series)

* For vehicles with an engine power of 110–150 horsepower. ** In parentheses—approximate ratio of fuel prices per unit of mass, data for 2022.

Table 1 shows a comparison of the basic parameters of conventional gasoline vehicles, hydrogen combustion vehicles and vehicles powered by hydrogen fuel cells.

Hydrogen in internal combustion engines has many advantages in terms of combustion properties. However, there is still a need for further research work that would improve several properties of hydrogen combustion vehicles, such as engine efficiency, power output, brake thermal efficiency, brake power, brake specific fuel consumption, range and reduction of NO_x emissions. Hydrogen combustion vehicles and hydrogen fuel cell vehicles have similar emission profiles—the main product of hydrogen fuel is water. However, in the case of hydrogen combustion engines, there is a trace of CO_2 emissions (from ambient air and lubrication oil). In addition, due to the higher combustion temperature, hydrogen combustion vehicles show the same or up to 20% higher NO_x emissions compared to gasoline vehicles. At the same time, it should be noted that NO_x emissions can be reduced by the use of an exhaust gas recirculation (EGR) system due to the dilution effect, which reduces the oxygen concentration in the intake charge or by the use of a selective catalytic reduction (SCR) system by catalytically reducing nitrogen oxides in the exhaust gas using ammonia as a reducing agent [18,23]. In the case of fuel cell vehicles, the emission of pollutants is lowest as compared to other vehicles. The purity of the hydrogen fuel is also an important issue. Fuel cell vehicles require high-purity hydrogen fuel (poisoning e.g., by sulfur compounds can affect the performance of the fuel cell). The basic hydrogen fuel impurity limits for FC vehicles are, respectively: 300 μmol/mol for non-hydrogen gases, 0.2 μmol/mol for carbon monoxide, and 0.004 μmol/mol for sulfur compounds. In the case of hydrogen combustion vehicles, it is possible to use hydrogen of lower purity, and the limits are as follows: 20,000 μmol/mol for non-hydrogen gases, 1 μmol/mol for carbon monoxide, and 2 μmol/mol for sulfur compounds [24]. Moreover, fuel cell vehicles require additional space to install the battery, which increases the production costs and weight of the vehicles. Oxidation processes in fuel cells also require certain amounts of catalysts that contain platinum metals. These metals increase the total cost of fuel cell production; moreover, current demand exceeds availability. In 2020, world production of platinum was about 160 tons, while the amount of platinum necessary to produce a fuel cell vehicle is in the range of 20–40 g. Assuming that the entire amount of mined platinum would be used for vehicle production, this would enable the production of about 5.5 million fuel cell vehicles, which is equivalent to only 0.5% of all vehicles in the world [12,16,25]. Developing both FC and ICE will be justified and may be carried out simultaneously. Total replacement of fossil fuel-based transportation might be easier to achieve only with fuel (hydrogen or hydrogen mixtures) ICE applications than producing whole new vehicles containing FCs. Hydrogen combustion engines and hydrogen fuel cell shave different levels of maturity. They are not in competition with each other, as both are driving the development of a common hydrogen production, transport, distribution and storage infrastructure. They are complementary technologies that share a role in reducing vehicle emissions.

3. The History of Hydrogen Combustion Vehicles

The use of hydrogen in cars is not a new approach. The history of hydrogen as a fuel for internal combustion engines is more than 200 years old [26]. In general, the interest in hydrogen as a fuel can be divided into several historical periods. The first mention of the hydrogen-powered engine dates back to the early 19th century. In 1807, François Isaac de Rivaz from Switzerland invented and designed the first hydrogen–oxygen combustion engine. Rivaz used an experimental combustion engine to drive a prototype vehicle over short distances, making it the first vehicle with an internal combustion engine [27]. The Rivaz engine had no timing mechanism, so the fuel injection and ignition were controlled manually, while a Volta cell was used to generate an electric spark [28]. The idea of igniting the fuel mixture by means of an electric spark was thus identical to that of modern combustion engines [8]. In 1820, Rev. W. Cecil presented to the Cambridge Philosophical Society a paper titled "On the Application of Hydrogen Gas to Produce Moving Power in Machinery" [29]. Cecil's gas engine was a vacuum engine, and it ran satisfactorily [30,31]. Since the beginning of the 19th century, many designs of various types of internal combustion engines and their components have been developed. The decisive year was 1860, when Belgian inventor Etienne Lenoir built the first useful small horizontal gas engine [32]. It was a single-cylinder, two-stroke engine powered by hydrogen gas generated by the electrolysis of water [33]. The engine was water-cooled and achieved an output of 0.7 kW at 80 rpm [34]. Later, Lenoir adapted the engine to use various other gases, such as coal gas. In 1863, a vehicle powered by Lenoir's engine completed a test drive over the 9 km between Paris and Joinville with an average speed of 3 km/h [35]. The engine was a big economic success, and more than 400 units were sold, while the whole thing was a huge step forward for automotive technology [34]. Despite initial success in the development of hydrogen-based engines, in later years they were not widely implemented, as they lost the competition with engines based on fossil fuels. Hydrogen combustion engines of that time were less efficient than hydrocarbon engines, and the storage of hydrogen in vehicles was a major problem. On the other hand, hydrocarbon fuels were a by-product of the oil companies that produced kerosene for lamps and heating in large quantities at the end of the 19th century. The fact that crude oil was already produced by a large industry using proven extraction and refining methods made it much cheaper than hydrogen as an automotive fuel. Despite this, the research on hydrogen vehicles was continued. As a result of World War I and II, significant progress was made in the technology for hydrogen-fueled vehicles. Increased fuel demand and the risk of cutting fossil fuel supplies have prompted national governments to invest in research into the use of hydrogen in transport. Another hydrogen car was invented in 1933 [36]. The Norwegian hydropower plant Norsk converted a small truck to run on hydrogen gas. The truck transported an ammonia reformer, which extracted hydrogen and then burned it in an internal combustion engine [37]. One of the first and most significant engineers to deal with a hydrogen-powered internal combustion engine was Rudolf Erren. In the 1920s, he began researching the modification of the Otto and diesel engines produced at that time. Rudolf Erren studied hydrogen as a fuel and conducted extensive experiments on hydrogen-powered engines [38]. He converted a number of gasoline and diesel engines to direct hydrogen injection. Modified Erren engines were used, among others, in trucks, buses and submarines [39]. Erren began his work in Germany; unfortunately the records of his research were completely destroyed by the Allied bombings of Berlin [31]. Later, he continued his work in England. The paper Erren and Campbell presented at the Institute of Fuel in London provided extremely optimistic data on brake thermal efficiency of as high as 60% in a hydrogen–oxygen engine incorporating steam recirculation. According to the director of the "Deutsche Erren Studiengeselleschaft", in Erren's engines, there were no problems with ignition, but the patented system required special fuel injection and control mechanisms to inject hydrogen [31]. Many other researchers have also worked on hydrogen engines. Interestingly, the first installations of hydrogen-powered internal combustion engine in Russia were used in 1941 during the siege of Leningrad (currently Petersburg). For urgent needs, the Russian Boris Shelishch converted 200 GAZ-AA trucks to using hydrogen, which burned cleaner and worked longer than those powered by gasoline [40]. Another return to interest in hydrogen engines took place in the 1970s, mainly due to environmental degradation due to fossil fuel exhaust emissions [41]. In 1966, Roger Billings converted the Ford A to hydrogen with a combustion engine, which was the flagship for hydrogen combustion engines [42]. In the years 1971–1978, test vehicles with hydrogen combustion engines were developed in Japan at the Musashi Institute of Technology and in Germany at Mercedes-Benz and DFVLR (German Aerospace Center, *ger. Deutsche Forschungsanstalt für Luft- und Raumfahrt*) [9]. In 1974, the Musashi Institute of Technology introduced the first Japanese hydrogen vehicle with a 4-stroke hydrogen engine and a high-pressure storage tank. In 1975–1977, Musashi Institute introduced hydrogen vehicles with a 4-stroke hydrogen engine in combination with a liquid hydrogen storage tank and with a 2-stroke spark ignition engine with hydrogen direct injection (DI). In 1984, the Musashi-6 with a late direct cylinder injection system and liquid hydrogen delivery system was presented at the WHEC-5 conference in Toronto [43]. The DFVLR research has significantly contributed to the development of liquid hydrogen tank technology for automotive applications. In 1979, BMW (*ger. Bayerische Motoren Werke*) introduced its first hydrogen vehicle in collaboration with DFVLR [9]. Between the 1970s and 1990s, BMW and Mazda began to develop several commercial hydrogen-powered combustion vehicles. The 20th century contributed to the development of hydrogen engine technology and demonstrated the possibility of using hydrogen in existing engine designs without major modifications to the original parts [41]. In the 21st century, we are seeing increasing interest in this type of vehicle, with many new models being developed.

4. Dedicated Hydrogen and Bi-Fuel Vehicles

Vehicles with hydrogen internal combust engines generate power through the combustion of hydrogen using fuel and injection systems based on the well-known technology of gasoline engines. For this reason, hydrogen-powered vehicles represent a relatively straightforward and promising path to move away from fossil fuels in the automotive industry. It should be noted that in addition to eliminating the problem of carbon dioxide emissions, the use of hydrogen as a fuel in an internal combustion engine brings with it a number of other advantages. Hydrogen has a high octane number (above 130) and a very high auto-ignition temperature; therefore, it has a high resistance to knocking combustion [12,14]. For the same reasons, the performance of a hydrogen-fueled engine is less sensitive to changes in the shape of the combustion chamber, level of turbulence and the intake charge swirling effect. The thermodynamic properties of hydrogen favor high compression temperatures that contribute to improvements in engine efficiency. On the other hand, due to the high hydrogen flame speed, shorter quenching distance of flame and higher thermal conductivity compared to hydrocarbons, the heat losses are higher than in gasoline operation, thus negatively affecting the efficiencies of hydrogen combustion engines. The undoubted advantage of hydrogen fuel is the fact that, due to the gaseous state of the fuel, it offers excellent cold starting ability and engine operation [14,15]. Moreover, when considering the economic considerations of fuel production, it should be remembered that unlike most fuel cells, the spark ignition engine is quite tolerant to fuel of lower purity [15,17,44].

However, the use of hydrogen as a fuel in an internal combustion engine requires a number of significant modifications. The most important are the issues related to ignition, fuel injection and compression. The first one concerns the ignition of the fuel mixture, namely the spark plugs. In a hydrogen internal combustion engine, it is necessary to use cold rated spark plugs so that spark plug electrode temperature avoids exceeding the auto-ignition limit and causing backfires. At the same time, it is not advisable to use spark plugs with platinum electrodes, since platinum is a catalyst for the oxidation of hydrogen [10,18,45,46]. It is also necessary to use grounding or a properly designed ignition system to avoid uncontrolled ignition due to residual ignition energy [9]. Another important issue is the fuel injection system. In the case of combustion engines powered by hydrogen, the optimal and most efficient solution in the field of fuel injection is direct injection (DI). DI can eliminate the tendency of an engine to backfire in the intake manifold and minimizes pre-ignition because fuel residence time in the cylinder can be shorter (a reduction in the risk of backfire and pre-ignition can also be achieved by optimizing the intake design). A hydrogen engine using DI has a power output of 20% more than a gasoline engine because the stoichiometric heat of combustion per kilogram of air is higher for hydrogen. In practice, we distinguish two basic sub-technologies. The first one is low-pressure direct injection (LPDI), where fuel injection occurs when the intake valve is closed and the pressure in the cylinder is low. The second one is high-pressure direct injection (HPDI), where fuel injection occurs at the end of the compression stroke [6,14,15,46–48]. The compression ratio is an equally important issue. As in other combustion engines, this parameter is optimized for highest efficiency. In the case of hydrogen-fueled combustion engines, the compression ratio may have higher values than for gasoline engines (depending on the application and engine design, it ranges from 7.5:1 to 14.5:1) [10,15,45,46,49].

Hydrogen combustion engines are an interesting solution in the field of combustion vehicles, but it was only in the first decade of the 21st century that many commercial vehicles came on the market. It should be noted that the current review covers both dedicated hydrogen vehicles (vehicles specifically designed and built for hydrogen operation by an original equipment manufacturer engine powered only by hydrogen) and bi-fuel vehicles, where the engine is equipped with two separate fuel systems allowing the vehicle to operate on gasoline as well as hydrogen. Due to the hydrogen on-board storage system, hydrogen vehicles can also be grouped as compressed hydrogen and cryogenic liquid hydrogen vehicles. The leading manufacturers of hydrogen internal combustion engine vehicles include brands such as: Ford, BMW, Mazda, Chevrolet and Toyota. Table 2 summarizes the most important technical parameters of the hydrogen-powered vehicles produced in the 21st century.

Table 2. Basic parameters of hydrogen combustion vehicles produced in the 21st century [9,15,46,50–54].

Model	Year	Engine	Type (Fuel)	Hydrogen Tank	Range (km)	Units Made
Ford P2000	2001	ICE 2.0 l straight-four engine Zetec (port injection)	Hydrogen	Compressed (87 dm^3, 250 bar, 1.5 kg)	100	
BMW Hydrogen 7	2003	ICE 6.0 l V12 (12-cylinder engine with high-pressured DI)	Bi-fuel (hydrogen/gasoline)	Cryogenic (8 kg)	200 (hydrogen) + 480 (gasoline)	about 100
Mazda RX-8 Hydrogen RE	2003	Twin-rotary Wankel rotary engine 1.3 l	Bi-fuel (hydrogen/gasoline)	Compressed (350 bar, 2.4 kg)	100 (hydrogen) + 500 (gasoline)	over 30
Ford Shuttle Bus	2004	ICE 6.8 l V10 Triton	Hydrogen	Compressed (350 bar, 29.6 kg) *	240–320	
ETEC Chevrolet Silverado	2004	ICE 6.0 l V8	Hydrogen	Compressed (3 × 150 dm^3, 350 bar, 10.5 kg) *	230–260	about 20

Table 2. *Cont.*

Model	Year	Engine	Type (Fuel)	Hydrogen Tank	Range (km)	Units Made
Toyota Quantum Prius	2005	ICE 1.4 l straight-four engine (electronic multi-point hydrogen injection)	Hydrogen	Compressed (1.6 kg)	100–130	over 30
Volkswagen Polo-converted	2011	ICE 1.4l straight-four engine (port injection)	Bi-fuel (hydrogen/gasoline)	Compressed (2 × 18 dm^3, 200 bar)	~400 (hydrogen)	1 (experimental)
Toyota Corolla (racing vehicle)	2021	ICE 1.6 l 3-cylinder turbo with intercooler	Hydrogen	Compressed		
Lexus RC F	2022	ICE 5.0 l V8	Hydrogen			designed vehicle

* The relatively higher fuel consumption is due to the correspondingly larger size and weight of the vehicle.

From the point of view of the scale of production, the BMW Hydrogen 7 (Figure 1a) is particularly noteworthy. It is the first mass-produced hydrogen-powered vehicle. The BMW 7 twelve-cylinder engine is equipped with two separate fuel systems, allowing the vehicle to run on both gasoline and hydrogen. Based on the BMW Hydrogen 7 (bi-fuel), a BMW Hydrogen 7 Mono-Fuel demonstration vehicle was developed, which runs on hydrogen only [9,15,52,55]. Another similarly known vehicle is the five-seater Ford P200 sedan, presented in 2001 with a two-liter engine equipped with highly optimized hydrogen port injection, powered by 250 bar compressed hydrogen from two carbon-fiber reinforced aluminum tanks [10,15,46]. Three years later, Ford fully engineered a demonstration fleet of 30 E-450 shuttle buses [9,56].

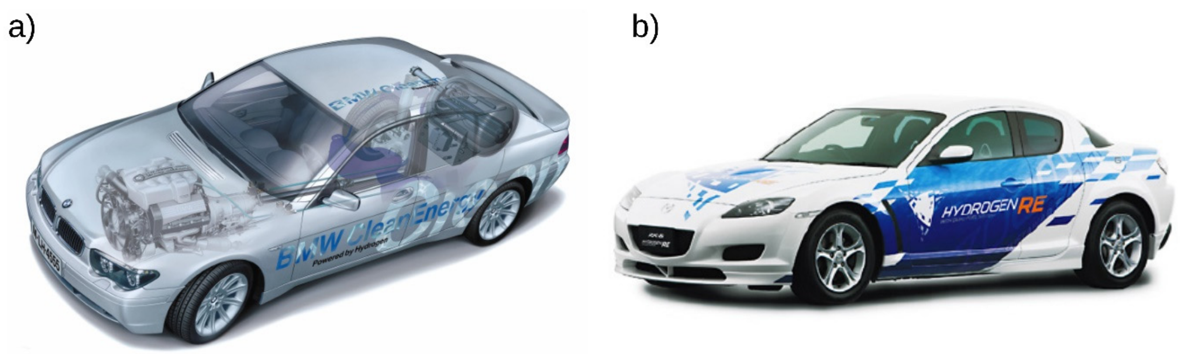

Figure 1. BMW Hydrogen 7 [57] (**a**) and Mazda RX-8 Hydrogen RE [9] (**b**).

Another interesting solution is Mazda's RX-8 Hydrogen RE (Figure 1b), with a hydrogen Wankel rotary engine supplied with hydrogen gas by an electronically controlled DI system. In this case, the use of a Wankel rotary engine (Figure 2) is particularly advantageous because it uses separate chambers for induction and combustion, which reduces the problem of backfiring often faced when using hydrogen in piston engines [15,58,59]. In recent years, the interest in the practical application of hydrogen combustion engines has been demonstrated by Toyota Motor Corporation (TMC). In 2021, TMC presented a racing vehicle based on Toyota's Corolla Hatchback with a 1.6-L internal combustion engine powered by compressed hydrogen. The vehicle took part in the Super Taikyu Series race [53,60]. In turn, in 2022 the companies Yamaha Group and Toyota Motor Corporation reported that they were working on a prototype 5-L hydrogen engine based on a Lexus RC engine with an assumed output of 450 horsepower [54,60].

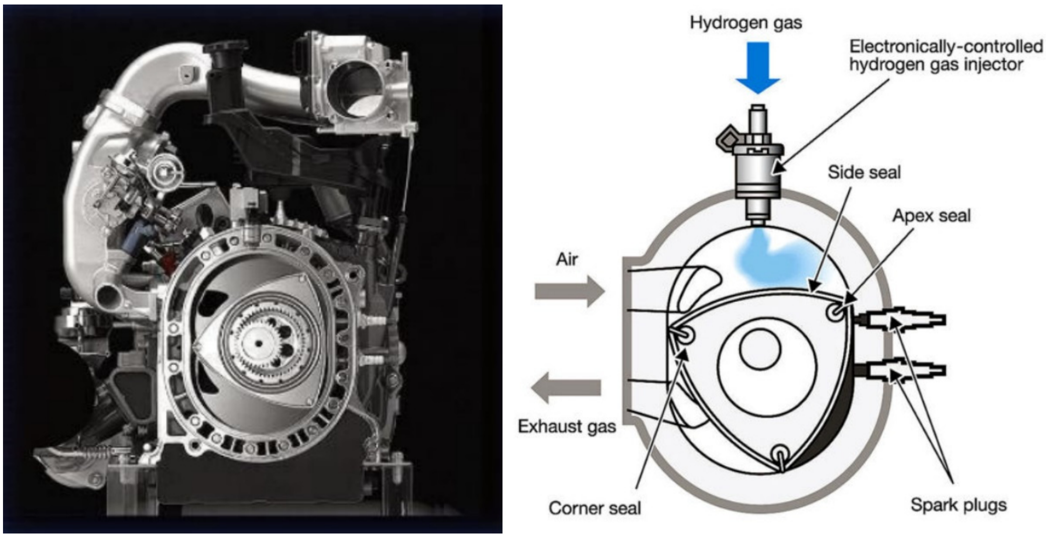

Figure 2. Cross-sectional diagrams of the hydrogen Wankel rotary engine [58].

5. Hydrogen in Combination with Other Fuels (Dual-Fuel Applications)

Another development direction in order to reduce pollutant emissions involves combustion engine technologies using alternative fuels and fuel blends. Fuel blends based on ethanol, methanol or water for gasoline engines [61,62] or blends based on ethanol or glycerol-based ethers for diesel engines [63,64] are an important issue in this area. This direction of development also makes it possible to use hydrogen as a fuel additive for conventional internal combustion engines. Hydrogen enrichment of coal fuels has been proposed mainly as a transition solution towards a full-fledged hydrogen economy. On the one hand, the presence of hydrogen may have a beneficial effect in increasing overall combustion stability [65]; on the other hand, the use of hydrogen-enriched fuels may contribute to alleviating the severe safety issues related to the use of pure hydrogen [66,67]. The idea of mixing hydrogen as a a fuel additive for standard internal combustion engines is based on the unique properties of hydrogen, i.e., low ignition energy, wide inflammability limit and superb combustion rate. Hydrogen, like any gas, fills the volume of the combustion chamber much faster than an atomized liquid fuel (high propagation speed). The hydrogen–air mixture is formed more easily and can be ignited using low energy (ca. 0.02 mJ) and takes place at a combustion rate several times greater than the combustion of hydrocarbons. Thanks to this, by introducing the addition of hydrogen, it is possible to improve the combustion parameters of a hydrocarbon fuel. In effect, it is observed that the fuel mixture burns efficiently with less unburnt residues, and higher combustion temperature is achieved, which improves energy conversion efficiency [68,69]. Hydrogen blending was examined with all common engines and fuels [15]: gasoline [68,69], diesel [26,70–73], liquid petroleum gas (LPG) [74,75], natural gas (liquefied natural gas/compressed natural gas, LNG/CNG) [76–78], and alcohols [79]. In general adding hydrogen to the combustion chamber can be realized by port fuel injection or DI. High-temperature hydrogen auto-ignition (535 °C) is required in the case of a compression ignition engine using spark plugs to start the burn process or requires the procedure of preignition (pilot ignition), i.e., backfire of small amount of compressed diesel fuel [70]. In the case of gasoline engines, studies indicate [80] that hydrogen blending has a positive influence on exhaust emissions and efficiency [81]. Decreased concentration levels are observed in the case of unburned hydrocarbons, CO, and CO_2. It is especially important in harsh working conditions of the engine, such as during idling or cold starts, when temperature and manifold absolute pressure in the combustion chamber are lower than in nominal conditions and influence incomplete fuel burning [82]. In some cases, the emission of nitrogen oxides (NO_x) is accelerated and rises with the temperature of fuel combustion in the air, which takes place, for example, in lean burn conditions [83,84]. Therefore, special emphasis should be placed on the control of hydrogen combustion conditions, especially if there are factors increasing the temperature. Reduction of NO_x emissions can be achieved by blending hydrogen with fuel, together with an increase in the air-to-fuel ratio (λ). Ji et al. [85] investigated increasing lean burn conditions up to $\lambda > 1.4$, connected with adding hydrogen to a volume fraction of 6%, which can keep NO_x emissions at the same level as achieved in stochiometric burning conditions and simultaneously reduce the remaining exhaust emissions. Hydrogen addition to the fuel does not disturb the performance of pollutant emission reduction systems such as EGR, diesel particulate filter (DPF) or SCR installed in modern cars, so the final emissions of a dual-fuel engine can meet the present challenging emission standards. Boreetti et al., in their publications [72,73], refer to many interesting studies regarding the workings of a diesel–hydrogen dual-fuel engine, e.g., adoption of a water injector to control the temperature of gases within the cylinder and the turbine at higher loads.

For now, standard cars powered by hydrogen combustion engines or bi-fuel engines are still a solution for the future. Currently, the addition of hydrogen is used in engines with the help of amateur solutions using generators of oxy-hydrogen gas, commonly known as Brown's gas or HHO. This solution has been known for many decades, and thanks to its simplicity and relatively low cost, it arouses considerable interest among amateurs of alternative fuels [86–88]. The oxy-hydrogen gas is a mixture of oxygen and hydrogen with a volume composition of 1:2 produced by alkaline electrolysis. The simplest car installation consists of a small electrolyser, usually made of stainless steel electrodes, and is powered by a car alternator. The system as a whole is located in the engine compartment. Research on these types of solutions shows that the positive effect of HHO addition to the combustion process may translate into a potential increase in engine performance of up to several percent [89–92]. This improvement is measured by thermal efficiency and a reduction in fuel consumption. Additionally, one can expect a reduction in pollutant emissions of CO, CO_2 and unburned hydrocarbon. According to reports, the emission of NO_x is ambiguous [86]. The increase in NO_x emissions is often explained as the result of an increase in the temperature of the fuel combustion. On the other hand, adding oxy-hydrogen gas into the engine can reduce the amount of fuel in the intake and create a lean burning condition in which the flame temperature is lower [89].

6. Conclusions and Perspectives

Utilizing renewable sources of energy for hydrogen production may become widespread and commonplace, allowing realistic zero-emission goals to be met. It will make hydrogen the fuel of the future. Hydrogen infrastructure and the distribution and storage of hydrogen, which are a key problem for hydrogen-powered vehicles, are becoming more cost-effective and practical, thanks to the introduction of legislation.

Those facts give hope for accelerating the development of vehicles powered by hydrogen internal combustion engines as a simple and low-cost solution. The progress in the technology for hydrogen combustion-powered vehicles was presented, examples of which were vehicle prototypes with a description of their basic technological parameters. The interest in this subject among leading manufacturers in the automotive field is visible, especially in the area of modernization of power systems in passenger cars. In addition, because hydrogen engine drivelines are mechanically very similar to traditional drivelines, these engines are also a great option for operators who drive in difficult conditions or who want predictable maintenance and service costs. Among the most promising prospects for the development of hydrogen engines are applications that do not require a dense refueling network, such as construction sites or farms. Vehicles on construction sites or in agriculture operate in aggressive duty cycles in harsh environmental conditions for months or years. The possibilities for local hydrogen storage, regional distribution centers, or local hydrogen production, e.g., the installation of electrolysers for the production of hydrogen, would solve the problem with hydrogen refueling in this case. Hydrogen engines in vehicles as well as construction equipment would contribute to reducing CO_2 emissions in urban areas.

In summary, hydrogen combustion vehicles offer many advantages. They are characterized by high tolerance to the quality of the hydrogen used, able to work in harsh environmental conditions, reliable and comfortable from the user's point of view, and to a large extent, they are a developed and proven technology, at the same time ensuring the independence of the automotive industry, due to lack of the need to use precious metals and rare earth metals. A disadvantage of hydrogen engines, however, is the release of nitrogen oxides and, as a result, they require exhaust gas treatment to reduce NO_x emissions. The opportunity to accelerate the development of the market for vehicles with a hydrogen combustion engine and to develop, in a short time, specific solutions for the transport sector, including vehicles with a diverse set of work cycles and applications, still depends on progress in the development of the broadly understood hydrogen infrastructure, as well as the introduction of appropriate legal regulations in this regard.

Author Contributions: Conceptualization, K.W. and J.W.; investigation, K.W., J.W. and W.T.; writing—original draft preparation, K.W., J.W. and W.T.; writing—review and editing, K.W., J.L., K.P. and A.C.; visualization, K.W.; supervision, K.W. and A.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Łukasiewicz Research Network—Industrial Chemistry Institute and the Łukasiewicz Research Network—Institute for Engineering of Polymer Materials and Dyes. The APC was funded by the University of Warsaw.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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