Mechanics Transport Communications
Academic journal http://www.mtc-aj.com
ISSN 1312-3823 (print)
ISSN 2367-6620 (online)
volume 22, issue 2, 2024
article № 2633

POWERING MOTOR VEHICLES – HYDROGEN VS. METHANE

Zoran Čekerevac
zoran@cekerevac.eu

MESTE
Knez Mihailova 33, 11000 Belgrade
SERBIA

***Key words**: motor vehicles, methane, hydrogen, internal combustion engines, fuel cells, air pollution, risks*

***Abstract:** This paper analyzes various propulsion systems, including internal combustion engines (ICEs) using hydrogen and methane, as well as hydrogen fuel cells. It primarily focuses on fuel cells that convert chemical energy from hydrogen and oxygen into electrical energy through electrochemical processes, providing a clean and efficient energy source. The paper details the materials and reactions involved, highlighting the roles of catalysts and the Fuel Cell Control Unit (FCCU) in managing the process. Despite their environmental benefits and high efficiency, hydrogen fuel cells face significant barriers to widespread adoption, including limitations in infrastructure, high production costs, and consumer perception issues. Safety concerns, such as the risks associated with invisible flames and high-pressure hydrogen storage, are also addressed. A comparative analysis of gasoline and methane-powered vehicles underscores the potential of hydrogen as a sustainable alternative, although challenges in production, storage, and infrastructure persist. The paper concludes that hydrogen fuel cells hold promise for reducing emissions and advancing sustainable transportation. Overcoming these barriers will require substantial investment in technology and infrastructure development; until then, methane remains a viable solution for reducing pollution.*

1 INTRODUCTION

While methane is a direct energy source, hydrogen primarily serves as an energy carrier, except in potential future nuclear fusion plants using deuterium and tritium. However, such production is still far from commercial viability. Currently, when hydrogen is produced from solar, biological, or electrical sources, it requires more energy to produce than it releases during combustion, making it more akin to a battery for energy storage. [1]

Despite this, hydrogen is increasingly viewed as an alternative fuel for powering motor vehicles due to its environmental benefits and efficiency. While it can be used in internal combustion engines, it is now more commonly utilized in fuel cell vehicles. Fuel cells convert hydrogen into electricity through a chemical reaction with oxygen, releasing only water as a byproduct. This makes hydrogen vehicles significantly cleaner compared to traditional vehicles that rely on fossil fuels.

Methane, also known as natural gas, is gaining traction as an alternative fuel due to its environmental advantages over traditional fuels like gasoline or diesel. When used in internal combustion engines, methane is typically in compressed form (CNG - Compressed Natural Gas) or liquid form (LNG - Liquefied Natural Gas[1]). Methane burns in the engine, releasing energy, carbon dioxide (CO_2), and water (H_2O). Due to its higher hydrogen-to-carbon ratio, methane reduces CO_2 emissions compared to conventional fuels.

2 CHARACTERISTICS OF HYDROGEN AND METHANE

To better understand the potential of hydrogen and methane as fuels for powering motor vehicles, Table 1 compares their basic characteristics.

Table 1 Hydrogen and methane basic characteristics[2]

Characteristic	Hydrogen	Methane (Natural Gas)
Chemical formula	H_2	CH_4
Molecular Weight	2 Da (2 g/mol)	16 Da (16 g/mol)
Flammability Limit	4% / 75%	7% / 20%
Adiabatic Flame Temperature in air at 1 atmosphere	2,127 °C (2,400 K) [2]	2,055 °C (2,328 K) [2]
Flame Speed at standard pressure and temperature	~ 2-3 m/s	~ 0.3-0.4 m/s
Lower Heating Value by Weight	120-142 MJ/kg [3]	50 MJ/kg
Volumetric Lower Heating Value	10.8-12.6 MJ/m³	35-39 MJ/m³

Source: Authors, based on [3] and [2]

Hydrogen is a pure element, while methane is a compound consisting of carbon and hydrogen. When hydrogen combines with oxygen during combustion, water vapor (H_2O) is the main byproduct. In contrast, the combustion of methane produces carbon dioxide (CO_2) and H_2O. Therefore, hydrogen combustion is considered a "clean" alternative to methane.

As the first element on the periodic table, hydrogen is very light, and its small molecules have a higher potential for leakage when used as a fuel. This necessitates careful consideration when selecting gaskets, valves, and seals. The methane molecule is significantly larger, with a molecular weight of 16, resulting in less pronounced sealing challenges.

For a fuel-air mixture to be combustible, a suitable fuel concentration in the air is required. Hydrogen can ignite if its concentration in the mixture is between 4% and 75%. For methane, the flammability limits are between 7% and 20%.

When hydrogen burns in air, the stoichiometric air-to-fuel ratio (AFR) is approximately 34:1, indicating that 34 parts by mass of air are needed for 1 part of hydrogen for complete combustion. This corresponds to the full reaction of 2 molecules of hydrogen and 1 molecule of oxygen.

Hydrogen can combust over a wide range of air-fuel ratios. When the AFR exceeds 34:1, a lean mixture forms, resulting in excess air, complete combustion of hydrogen, maximum water production, and increased NO_x emissions. Conversely, if the AFR is less than 34:1, there is more hydrogen relative to the available oxygen, leading to incomplete combustion, lower combustion temperatures, and reduced emissions of water and nitrogen oxides. Rich mixtures typically have AFRs ranging from 20:1 to 34:1. In real-world conditions, emissions can vary based on current combustion conditions, temperature, pressure, and the presence of other gases. Optimizing the AFR is crucial for achieving efficiency and reducing emissions.

---

[1] LNG is most used in maritime transport (e.g., LNG-powered ships) and in some heavy-duty trucks, while CNG is more suitable for vehicle engines primarily due to storage methods.

[2] Standard conditions here refer to a temperature of 15°C (approximately 288 K) and a pressure of 1 atm (101.325 kPa). These standard conditions allow for consistent comparison of the energy values of different fuels. [15]

[3] For comparison, 1 kg of hydrogen is equivalent to 3.3 kg of gasoline (based on the lower heating value) [14]

Methane combusts with a stoichiometric air-to-fuel ratio of about 17.2:1 by weight (i.e., 17.2 parts by weight of air for each part of methane). At this ratio, complete combustion ideally occurs, forming only carbon dioxide (CO_2) and water (H_2O).

When burning a lean mixture with an air-to-fuel ratio (AFR) greater than 17.2:1, complete combustion of methane can be expected due to the presence of excess oxygen. However, the combustion can be prevented under unfavorable conditions such as fuel shortages, kinetic factors, and possible intermediate products. That is especially true for leaner mixtures. Burning a lean mixture of methane can produce higher nitrogen oxides (NO_X) emissions due to elevated temperatures. Conversely, with AFRs less than 17.2, burning rich mixtures results in incomplete combustion, increased carbon monoxide (CO) emissions, and unburned hydrocarbons due to a lack of oxygen.

Both hydrogen and methane have optimal ratios for different applications, and engineers often use sensors and control systems to optimize combustion and reduce harmful emissions. In practice, operational ratios frequently differ from theoretical ones due to variations in combustion conditions.

The flame front speed of fuels, including hydrogen and methane, depends on several factors, including fuel concentration, the presence of an oxidizer (air or oxygen), pressure, temperature, and other environmental conditions:

- The combustion speed of hydrogen is maximal in a stoichiometric mixture.
- Increasing pressure leads to higher reactant density, resulting in faster reactions and increased flame speed.
- Increasing temperature can raise flame speed according to Arrhenius law, which states that the rate of a chemical reaction depends on temperature. At higher temperatures, reactants possess increased kinetic energy, leading to faster and more frequent collisions between fuel and oxygen molecules, thus increasing the rate of chemical reactions and combustion.
- Flame speed also depends on whether combustion occurs in an open space or a closed chamber and on the presence of other gases. That is particularly significant for fuel storage.

Under ideal conditions (stoichiometric mixture, standard pressure, and temperature), the flame front speed of hydrogen can reach 2 to 3 meters per second. Under certain circumstances or with the addition of other chemicals, this speed can further increase. The flame speed of hydrogen is nearly ten times that of methane (see Table 1). It is important to note that specific values may vary significantly depending on the exact conditions.

Increasing flame speed and enhanced fuel combustion can have positive and negative consequences, depending on the context in which combustion occurs. For instance, in engines, it can improve efficiency; however, in uncontrolled conditions, it may lead to hazards such as explosions or fires. The fast flame speed and wide combustion range of hydrogen make it harder to manage. Flame speed represents one of the more significant design considerations in hydrogen combustion, as managing the location of combustion becomes increasingly difficult. This issue is particularly pronounced when hydrogen is burned in a gas turbine combustor, where the flame tends to move upstream of the ideal combustion location, potentially leading to oscillating combustion phenomena or flashback – like a backfire in car engines.

The "adiabatic flame temperature" (AFT) is defined as the maximum temperature achievable through the combustion of a fuel with an oxidizer, assuming that no heat is lost to the surrounding environment (adiabatic condition). It is determined based on the stoichiometry of the reaction, the initial temperatures of the reactants, and the enthalpy changes involved in the response. The adiabatic flame temperature provides a crucial theoretical limit for combustion processes and is essential for understanding the efficiency and performance of fuels in various applications.

The adiabatic flame temperature of hydrogen under ideal stoichiometric conditions—when hydrogen combusts in a pure oxygen environment rather than in air—can reach approximately 2000°C to 3000°C. This temperature range is higher than that of natural gas, and not all materials can withstand such elevated combustion temperatures. Consequently, careful consideration must be given to material selection, heat dissipation, and cooling requirements.

When hydrogen is burned in the air, the increased flame temperature can lead to a greater formation of nitrogen oxides (NO_x) compared to the combustion of natural gas. This issue can be mitigated by modifying combustion parameters, such as adjusting air-to-fuel ratios, controlling hotspots within the flame, and enhancing emission treatment in the exhaust manifold. Selective catalytic reduction systems represent one viable option for reducing NO_x emissions.

The lower heating value (LHV), defined as the amount of heat released during the combustion of fuel without considering the latent heat of water vapor condensation, is a critical metric for understanding the energy density and efficiency of various fuels in energy systems. Common values of the LHV for hydrogen and methane are presented in Table 1. It is essential to recognize that the LHV can vary significantly based on several factors, including fuel purity and specific combustion conditions.

Given that hydrogen is less dense than natural gas, it requires approximately three times the volume to achieve the same amount of energy. Because storage capacity in vehicles is typically limited, this necessitates the use of higher pressures for the storage and supply of hydrogen to obtain equivalent energy output.

3 PRODUCTION OF HYDROGEN AND METHANE

Hydrogen and methane exhibit distinct characteristics, which influence their respective production methods. While methane can naturally occur, hydrogen must be manufactured through specific processes.

3.1 Methane Production

Methane (CH_4) can be produced through various methods, with the two most significant being natural fermentation (biogas production) and industrial synthesis.

- *Natural Fermentation (Biogas Production):* Methane can be generated via biological processes in biogas plants that process organic waste to produce methane as a renewable fuel. This biogas can be purified and utilized as fuel for internal combustion engines, thus contributing to a reduction in ecological footprint. The production process occurs under anaerobic conditions, where microorganisms decompose organic matter, including plant residues, manure, and other biological materials. As a result of this decomposition, complex organic substances are typically transformed into biogas that contains 50% to 70% methane, with the remaining composition comprising carbon dioxide and trace amounts of other gases.
- *Industrial Synthesis:* Methane can also be produced through a variety of chemical processes, the most notable of which is the Fischer-Tropsch synthesis. This method converts hydrocarbons, such as natural gas or crude oil, into methane using catalysts under elevated temperatures and pressures to facilitate the chemical reaction between carbon dioxide and hydrogen. Additionally, methane can be produced during the gasification of biomass or coal, wherein organic materials are combusted in environments with limited oxygen or hydrogen, generating synthetic gases that may contain methane.

The significance of methane production extends beyond its role as an energy source. It also serves as a crucial component in the chemical industry. Due to its comparatively lower environmental impact as a fuel, methane is increasingly recognized as a vital element in the transition towards more sustainable energy systems.

3.2 Hydrogen Production

The production of hydrogen suitable for powering motor vehicles can be accomplished through several methods, each with its cost-effectiveness determined by factors such as the technology employed, energy sources, and raw materials. Some of the most recognized methods for hydrogen production include:

- *Water Electrolysis:* This process involves the decomposition of water (H_2O) into hydrogen and oxygen using an electric current. When the electricity is derived from renewable energy sources, such as solar or wind power, this method can be environmentally sustainable. While the initial costs may be higher, the significant benefits of reducing harmful gas emissions position water electrolysis as a promising long-term solution for green hydrogen production.
- *Natural Gas Reforming:* Currently, this is the most prevalent method for commercial hydrogen production. The process entails a chemical reaction between natural gas (primarily methane) and steam, yielding hydrogen and carbon dioxide. Although this method is economically viable, it has adverse environmental impacts due to CO_2 emissions, which contribute to greenhouse gas effects.
- *Methane Pyrolysis*: Methane pyrolysis (CH□) involves the thermal decomposition of methane at elevated temperatures in the absence of oxygen, producing solid carbon and gaseous hydrogen. The chemical reaction can be expressed as follows: $CH_4 \rightarrow C + 2H_2$. The hydrogen concentration at the output of the methane pyrolysis unit can range from 50% to over 75%. Exact percentages depend on factors such as equipment characteristics, process optimization, and end-product specifications. On average, the energy consumption for producing hydrogen via methane pyrolysis is approximately 50-60 kWh per cubic meter of hydrogen. This energy requirement exceeds the energy output of hydrogen as fuel. However, advancements in technology and process optimization may enhance the energy efficiency of methane pyrolysis, reducing the overall production costs.
- *Biomass and Biogas*: Hydrogen can also be produced through techniques such as anaerobic digestion or biomass gasification, which utilize organic materials. This approach is generally considered sustainable, but its feasibility and cost-effectiveness are contingent upon local resource availability and conditions.
- *Thermal Water Splitting*: This process employs high-temperature methods, including solar energy in steam cycles, to decompose water into hydrogen and oxygen. Although still primarily in the research and development phase, this method holds promise for future applications.
- *White Hydrogen*: Recently, there has been increasing interest in extracting white hydrogen, a term for naturally occurring hydrogen trapped in the Earth’s crust. Extraction involves hydraulic fracturing, where a mixture of water, sand, and chemicals is injected into wells at high pressure to release hydrogen from geological formations. While this technology shows potential, it is not yet widely adopted due to high production costs (estimated between \$3 to \$8 per kilogram) and possible negative environmental impacts, such as methane emissions and water pollution.

Achieving economically viable hydrogen production necessitates a comprehensive assessment of local resources, energy costs, technological availability, and environmental considerations. Given the growing interest in hydrogen as a clean fuel, its role in reducing emissions and facilitating the transition to sustainable energy systems is becoming increasingly significant.

4 THE USE OF HYDROGEN AS FUEL FOR VEHICLES

4.1 Early Use of Hydrogen in Internal Combustion Engines

The first uses of hydrogen as a fuel for internal combustion engine vehicles can be traced back to the early 19th century when François Isaac de Rivaz invented the first hydrogen-oxygen combustion engine [4]. Following this invention, several other inventors made contributions to the development of internal combustion engines, including the renowned Nikolaus August Otto and Rudolf Christian Karl Diesel. In his 1874 novel *The Mysterious Island*, Jules Verne predicted the use of hydrogen as fuel, stating that "water will one day be employed as fuel, and that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable" [5]. This vision captivated many researchers, prompting them to investigate the potential of hydrogen. More significant applications of hydrogen were experimental in the 1930s and 1940s. During World War II, efforts were directed toward using hydrogen as a fuel for engines. For instance, Russian engineer Boris Shelishch converted about 200 GAZ-AA trucks to operate on hydrogen. These trucks exhibited cleaner and longer operations compared to those using gasoline [6].

In a more modern context, significant experimentation with hydrogen as fuel began in the 1970s and 1980s, when many companies and research institutes explored various possibilities of using hydrogen, including direct combustion in internal combustion engines and the use of fuel cells. A notable monograph from this period is "Neue Kraftstoffen auf der Spur" [7], which details the potential of using hydrogen to power vehicles. A more comprehensive overview of examples of hydrogen as a fuel for engines is provided in [6].

4.2 Fuel Cells

In the 1990s and beyond, with a growing interest in alternative fuels and environmentally friendly solutions, the development of hydrogen fuel cell vehicles became increasingly popular. Today, some car manufacturers, such as Toyota, Honda, and Hyundai, are focusing on hydrogen fuel cell vehicles as more sustainable transportation options.

4.2.1 How Do Hydrogen Fuel Cells Work?

Hydrogen fuel cells convert the chemical energy of hydrogen and oxygen directly into electrical energy using electrochemical processes. Fuel cells work differently from chemical cells. Fuel cells produce a voltage continuously if they are supplied with a constant supply of suitable fuel and oxygen. The fuel oxidizes electrochemically rather than being burned, so the reaction takes place at a lower temperature than if it were burned. Energy is released as electrical energy, not thermal energy (heat) [8].

The operation of fuel cells can be described through the following segments:

1. *Materials*: Hydrogen fuel cells use hydrogen (H_2) and oxygen (O_2) as primary inputs. Hydrogen is typically stored in pressurized tanks, while oxygen can be obtained, e.g., from the air.
2. *Electrochemical Reaction*: When hydrogen is introduced into the fuel cell, it passes through the anode (the negative electrode in this case). At the anode, hydrogen is split into protons (H^+) and electrons (e^-) in the presence of a catalyst. The catalyst can be platinum-based, Pt-alloys with iridium or ruthenium, or non-precious metals, such as iron or manganese nitrides, which have proven to be economical and cheaper alternatives to platinum. The reaction can be represented as $2H_2 \rightarrow 4H^+ + 4e^-$. No external energy is required to split hydrogen atoms at the anode in fuel cells; the process occurs spontaneously with the catalyst, allowing the reaction to proceed at lower temperatures without additional energy. [9] The Fuel Cell Control Unit (FCCU) manages this process by regulating current and voltage, maintaining optimal cell

temperature, removing water, and monitoring system components such as the hydrogen injector, electric air compressor, recirculation pump, and sensors [10].

3. *Movement of Protons and Electrons*: Protons (positive ions) pass through the electrolyte, which is typically a proton-conducting membrane (e.g., a polymer electrolyte membrane – PEM). This membrane allows protons to pass through but not electrons. Electrons travel through an external circuit, creating an electric current [11].
4. *Reaction with Oxygen*: At the cathode (the positive electrode in this case), electrons combine with protons and oxygen from the air to form water: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
5. *Electricity Production*: This process generates an electric current, which can be used to power electrical devices, including electric motors in cars.
6. *Products*: As a result of the entire process, the only by-products are water (H_2O) and heat, making hydrogen fuel cells an environmentally friendly technology. For fuel cells used in vehicles, large radiators, and air intakes must be provided to ensure adequate heat dissipation [12]. The operating temperature of fuel cells is lower than that of internal combustion engines, which can lead to cooling issues during hot summer days. Similarly, in extremely low winter temperatures, there may be challenges in heating the fuel cell to its minimum operating temperature. This situation is comparable to that of batteries in purely electric vehicles.

The construction of fuel cells can include various materials and technologies, but the basic principle of converting hydrogen and oxygen into electrical energy remains consistent. This makes them a promising energy source for various applications, including transportation, stationary power generation, and other industrial processes.

4.2.2 Barriers to the Mass Adoption of Fuel Cells in Vehicles

While hydrogen fuel cells offer numerous advantages, including environmental benefits and high efficiency, several significant challenges impede their widespread adoption in vehicles. These barriers include:

1. *Infrastructure*: One of the most significant challenges for adopting hydrogen as a fuel is the inadequate infrastructure for hydrogen production, storage, and distribution. Few refueling stations currently offer hydrogen, making it difficult for drivers to find convenient refueling options.
2. *Production Costs*: Producing hydrogen, particularly through electrolysis, can be costly and environmentally challenging, especially if it is not sourced from cheap renewable energy. Hydrogen production from fossil fuels, such as natural gas, releases CO_2 emissions, which diminishes its environmental benefits.
3. *Fuel Cell Costs*: Fuel cell technology and the materials used, such as platinum catalysts, contribute to the higher production costs of fuel cell vehicles compared to conventional electric or internal combustion engine vehicles.
4. *Storage and Transportation*: Hydrogen is lighter than air and easily disperses, making its safe storage and transport challenging. Storing hydrogen under high pressure or in liquid form requires specialized tanks.
5. *Efficiency and Range*: While hydrogen vehicles are generally efficient, they face range challenges compared to conventional synthetic fuels or electric vehicles. Battery electric vehicles have much more developed charging infrastructure.
6. *Consumer Perception*: There is a lack of understanding and trust in hydrogen *technologies* among consumers. Many buyers still prefer to rely on traditional fuels or battery electric vehicles. It also takes a certain amount of courage for a car driver to drive a tank that is under a pressure of 350 bar and more.

Addressing these challenges, along with innovations in technologies, can contribute to the broader acceptance of hydrogen fuel cells in the future, but it will likely require time and additional investments in infrastructure and research.

4.2.3 Safety of Using Fuel Cells in Vehicles

Fuel cell vehicles can pose fire risks like those of other vehicle types, particularly in the event of a collision. Understanding specific characteristics and safety measures is crucial for mitigating these risks:

1. *Invisible Flame*: Hydrogen ignition can produce flames that are difficult to detect due to their colorless nature. This feature could obstruct firefighters from quickly pinpointing the source of the fire in an emergency.
2. *Burning Speed*: Hydrogen burns rapidly, potentially leading to fast flame spread. If a leak occurs, immediate action is necessary to prevent the situation from escalating.
3. *Hydrogen Storage System*: Hydrogen Storage System: Hydrogen is stored under high pressure, often ranging from 350 bar to 700 bar, in robust, durable tanks designed to withstand significant impacts. These tanks undergo rigorous testing to ensure their safety and integrity. Safety mechanisms are activated during collisions to mitigate leak and explosion risks. Other storage methods exist, such as liquid hydrogen or chemical storage, but high-pressure gas storage remains the predominant choice for fuel cell vehicles.
4. *Leak Risk*: In the event of a collision, there is a possibility of hydrogen leakage. While hydrogen ignites easily and disperses quickly in the atmosphere, under normal conditions, the gas tends not to accumulate as other fuels do.
5. *Polymer Electrolyte Membrane (PEM)*: Fuel cells contain electrical components that can be susceptible to water exposure or short circuits, which may lead to fire risks. Similar vulnerabilities exist in electric cars[4] and, to a lesser extent, traditional internal combustion engine vehicles.
6. *Previous Experiences*: Although some incidents involving hydrogen vehicles have been reported, the overall incidence of fires linked to these vehicles is low compared to traditional gasoline and diesel engine cars.
7. *Training and Equipment*: Firefighters and emergency personnel require specific training to manage the unique fire risks associated with hydrogen. Specialized equipment may be necessary for effective response actions.
8. *Rules and Regulations*: Many countries enforce distinct protocols and guidelines for extinguishing fires involving hydrogen systems, which further enhances safety for responders.
9. *Regulatory Compliance Tests*: Fuel cell vehicles undergo extensive testing and certification before reaching the market, including crash simulations to ensure safety.

Overall, while hydrogen presents some distinct risks, adherence to stringent safety standards plays a key role in ensuring the safety of fuel cell vehicles and hydrogen storage systems.

---

[4] Recent hurricanes, Helen and Ian, have highlighted a vulnerability in electric vehicles when exposed to saltwater, which can lead to fires. Flooding from rising sea levels submerged many vehicles, including electric ones, resulting in a higher-than-average number of fires among them. Manufacturers advised owners to move their cars out of risk areas and not to use them if they have been submerged. Saltwater is a much better conductor than freshwater due to its high mineral ion content, which can cause short circuits in electric vehicle batteries. These short circuits can lead to overheating and fires, even after the battery has dried. During Hurricane Ian, between 3,000 and 5,000 electric vehicles were flooded, but only 36 caught fires, about 1% of the total. The problem is more pronounced when it is considered that it has been observed that fires can occur several weeks after the removal of salt water. Thus, after flooding with salt water, the car is no longer usable. Research is ongoing to find solutions to minimize the risk of fires caused by saltwater contact with batteries.

4.2.4 Comparative Characteristics of Gasoline and Hydrogen Propulsion

Table 2, for easier understanding, compares the basic characteristics of gasoline spark ignition engines and both variants of hydrogen-powered vehicles. A group of drives in the 82 to 112 kW range was considered, corresponding to the power needed for light passenger vehicles. In this summary, the most impressive aspect is the fuel consumption-cost ratio. According to this criterion, the gasoline engine is significantly superior.

Table 2 Comparative characteristics of gasoline and hydrogen propulsion

	Gasoline Vehicles	Hydrogen Vehicles	
Engine type	Internal Combustion Engine	Internal Combustion Engines	Hydrogen Fuel Cells Electric Motor
The efficiency of the propulsion system	mostly ~20–40% maximum >50	~40–50%	~45–55%
Fuel consumption *	approx. 5L (or 3.7 kg) of gasoline per 100 km	approx. 1.4 kg of hydrogen per 100 km	approx. 1.0 kg of hydrogen per 100 km
The current cost of fuel	low (~0.1)	high (~0.9)	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 82–112 kW (110–150 horsepower).
In parentheses is given the approximate ratio of fuel prices per unit of mass, data for 2022.
Source: [6] modified by the author.

5 USE OF METHANE AS FUEL FOR VEHICLES

Methane is gaining popularity due to its environmental and economic advantages. It can be produced from renewable sources, such as bioenergy or biogas, which helps reduce dependence on fossil fuels and enhances energy security. As highlighted in the introduction, methane powers motor vehicles in two forms: Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG). Each form has its advantages and disadvantages, which can be analyzed in comparison to traditional fuels like gasoline and diesel, as well as alternative fuels such as hydrogen.

Advantages of Methane:

- *Lower Emissions*: Methane produces significantly fewer harmful emissions compared to gasoline and diesel engines. Carbon dioxide (CO_2) emissions are notably reduced, while nitrogen oxides (NO_x) and particulate emissions are almost nonexistent. This makes methane a more environmentally friendly option, especially in urban areas where air quality and public health are priorities.
- *Cost-Effective*: Methane is often cheaper than gasoline and diesel, and methane engines typically have higher combustion efficiency, which can result in lower costs per kilometer. This factor is particularly important for commercial fleets and operators with many vehicles. Additionally, methane can generate higher torque, enhancing vehicle performance.
- *Longevity*: Methane engines tend to have a longer lifespan due to better mixture formation and cleaner combustion, which reduces wear on internal components.

Disadvantages of Methane:

- *Infrastructure*: One of the main challenges of using methane as a vehicle fuel is the lack of adequate refueling infrastructure. The limited network of CNG and LNG refueling stations can create practical difficulties for drivers in certain regions, hindering everyday use.

- *Storage*: Methane tanks are larger and heavier, which can reduce trunk space and increase vehicle weight.
- *Range*: Methane vehicles generally have a shorter range compared to gasoline and diesel vehicles, which can be a disadvantage for drivers who frequently travel long distances.
- *Safety* Risks: Methane is flammable and can present safety risks in the event of a leak. While modern refueling and storage systems are designed to be extremely safe, concerns about potential incidents persist.
- *Conversion* Costs: Vehicles converted to run on methane may require significant investment in equipment and modifications [13]. Furthermore, regular technical inspections and certifications are necessary, which can further deter drivers.

Comparison with gasoline and diesel engines:

- *Gasoline engines* are known for their flexibility and ease of maintenance, yet they produce more CO_2 emissions and have higher operational costs compared to methane.
- *Diesel engines* are more fuel-efficient and tend to have a longer lifespan. However, they emit more NO_x and particulates, making them less environmentally friendly.

Comparison with hydrogen engines:

Hydrogen engines produce only water vapor as emissions, making them the cleanest fuel available. However, the infrastructure for hydrogen refueling is even less developed than that for methane, and the costs associated with hydrogen production and storage remain high.

6 MAJOR MANUFACTURERS OF METHANE AND HYDROGEN-POWERED VEHICLES

6.1 Methane Vehicles

Several manufacturers globally offer vehicles powered by methane. Among them are:

1. *Volkswagen*: Models such as the Golf TGI and Caddy utilize Compressed Natural Gas (CNG) as fuel.
2. *FIAT*: The Panda, Doblo, and Fiat 500 are available with a CNG option.
3. *Škoda*: The Octavia G-TEC is a well-known methane-powered model.
4. *SEAT*: The Leon TGI is another model that runs on CNG.
5. *Mercedes-Benz*: Offers CNG options in its commercial vehicles and vans.
6. *Iveco*: Specializes in producing methane-powered trucks and buses.

6.2 Hydrogen-Powered Vehicles

Currently, several companies and manufacturers are engaged in producing hydrogen-powered vehicles, utilizing both internal combustion engines and fuel cells.

6.2.1 Internal Combustion Engine Manufacturers

Several companies are researching and developing internal combustion engines that operate on hydrogen. This technology closely resembles traditional gasoline engines, with hydrogen serving as the fuel. Here are a few examples:

1. *BMW*: Has experimented with hydrogen engines in its prototypes, developing models based on existing engine technologies.
2. *Mazda*: Explored the use of hydrogen in its internal combustion engines, with the RX-8 model as a notable prototype.
3. *Toyota*: Developed internal combustion engines capable of running on hydrogen as part of its research program.
4. *Gordon Murray Automotive*: Has expressed interest in developing hydrogen-powered engines.

While hydrogen internal combustion engine technology is still under development, many manufacturers are focusing on fuel cells as a more appealing and efficient alternative.

6.2.2 Fuel Cell Manufacturers

Manufacturers are increasingly focusing on fuel cells, recognizing their potential. Here are some notable examples of hydrogen fuel cell vehicles:

1. *Toyota*: A pioneer in hydrogen vehicles, with their Mirai model being one of the most recognized fuel cell vehicles.
2. *Hyundai*: Actively engaged in hydrogen technology with its NEXO model, powered by fuel cells.
3. *Honda*: Developed a hydrogen vehicle known as the Clarity Fuel Cell.
4. *BMW*: Exploring hydrogen technologies, with the BMW Hydrogen NEXT prototype utilizing fuel cells.
5. *Mercedes-Benz*: The GLC F-CELL combines fuel cells and batteries into a single system.
6. *Nikola Corporation*: Focuses on hydrogen and electric-powered vehicles, particularly in the commercial sector, such as trucks.
7. *Rimac Automobili*: While primarily known for electric vehicles, this company has also explored hydrogen options for high-performance cars.

In addition to these companies, numerous smaller manufacturers and startups are experimenting with hydrogen technology. The continued development of hydrogen refueling infrastructure, along with advancements in fuel cell technologies, is propelling the growth of the hydrogen vehicle market.

The environmental implications of these technologies play a crucial role in their future adoption. However, it is important to note that, at present, pollution has largely shifted from urban areas to other regions.

7 CONCLUSIONS

Compared to gasoline and diesel, methane offers clear environmental advantages, particularly in reducing harmful gas emissions. As a result, methane is already widely used in motorization, and its sources and production processes are key to its role as a more sustainable alternative fuel. The use of methane in this context presents several advantages: its combustion releases fewer particulates and nitrogen oxides (NO_x) compared to diesel and gasoline. Additionally, CO_2 emissions are lower per unit of energy, making methane an attractive choice in the fight against climate change. Although challenges related to infrastructure and storage exist, growing environmental awareness and the need to reduce emissions make methane a compelling alternative. Major car manufacturers recognize this potential and are increasingly investing in the development of methane-powered vehicles.

Hydrogen-powered vehicles represent another significant advancement in environmental performance, particularly at the point of use. When burned, hydrogen produces water and NO_x as by-products, while the only by-product of fuel cells using hydrogen is water. One of the main advantages of hydrogen is its high energy density per unit mass, allowing it to be stored in smaller spaces and providing a greater range compared to battery electric vehicles. Hydrogen tanks can also offer refueling speeds comparable to those of traditional internal combustion engine vehicles.

However, there are challenges associated with hydrogen. The production, transport, and storage of hydrogen necessitate complex and costly infrastructure. Currently, most hydrogen is produced from natural gas, which can result in CO_2 emissions. Sustainable hydrogen production methods, such as water electrolysis using renewable energy sources, represent pathways to reduce these emissions.

Safety is another vital consideration, as hydrogen is highly flammable and requires appropriate safety measures. Nonetheless, while there is a risk of fire in the event of a collision involving fuel cell vehicles, their design and safety systems help mitigate this risk. As with all vehicle types, proper use and maintenance are essential. With ongoing technological advancements and infrastructure development, hydrogen has the potential to become a key component of future transportation systems, especially in heavy-duty vehicles and public transportation, where its applications are currently being most thoroughly explored. Promoting hydrogen as a fuel can contribute to reducing pollution and transitioning to more sustainable forms of transportation.

However, it must be emphasized that even the most environmentally friendly solutions, on their own, will not resolve environmental pollution issues. Key changes are needed in public awareness and transportation organizations. Full attention should be given to public transport and the principles of shared mobility, such as car-sharing. Only through a reduction in car production and the number of passenger vehicles can we improve the situation regarding environmental preservation. However, this environmentally friendly approach brings with it challenges as it can threaten the automotive industry.

REFERENCES:

[1] J. McCarthy, Hydrogen, Stanford, CA: Stanford University, 1995.

[2] Princeton, "Thermodynamics Glossary - Adiabatic Flame Temperature," [Online]. Available: https://www.princeton.edu/~humcomp/sophlab/ther_37.htm.

[3] J. Koestner, "6 Things to Remember about Hydrogen vs Natural Gas," 20 08 2021. [Online]. Available: https://www.powereng.com/library/6-things-to-remember-about-hydrogen-vs-natural-gas.

[4] S. Ratiu, "The history of the internal combustion engine," *Annals of the Faculty of Engineering Hunedoara,* no. 1, p. 145–148, 2003.

[5] A. Finkel, "145 years after Jules Verne dreamed up a hydrogen future, it has arrived," 25 Nov 2019. [Online]. Available: https://theconversation.com/145-years-after-jules-verne-dreamed-up-a-hydrogen-future-it-has-arrived-127701.

[6] K. Wróbel, J. Wróbel, W. Tokarz, J. Lach, K. Podsadni and A. Czerwiński, "Hydrogen Internal Combustion Engine Vehicles: A Review," *Energies,* vol. 15, no. 23, p. 8937, 2022.

[7] Bundesministerium fuer Forschung und Technologie, Neue Kraftstoffen auf der Spur, Munich: Gersbach & Sohn Verlag, 1974.

[8] BBC, "Chemical cells - AQA: Fuel cells," 08 Mar 2018. [Online]. Available: https://www.bbc.co.uk/bitesize/guides/z2396yc/revision/2.

[9] J. Granholm, "Hydrogen and Fuel Cells 101," 26 Jan 2022. [Online]. Available: https://www.bosch-mobility.com/en/solutions/powertrain/fuel-cell-electric/fuel-cell-control-unit/.

[10] Bosch, "Fuel cell control unit," 19 Sep 2024. [Online]. Available: https://www.bosch-mobility.com/en/solutions/powertrain/fuel-cell-electric/fuel-cell-control-unit/.

[11] DoITPoMS, Proton Exchange Membrane Fuel Cells (PEMFCs), Cambridge: University of Cambridge, LibreTexsts, 2024.

[12] Bruce, "Keeping your cool isn't easy for batteries or fuel cells," 20 Jul 2015. [Online]. Available: http://www.catalyticengineering.com/keeping-your-cool-when-youre-a-battery-a-fuel-cell-or-an-engine/.

[13] Z. Čekerevac, Z. Dvořák, and L. Prigoda, "Electric or Internal Combustion Engines for Passenger Cars? – Environmental and Economic Aspects," *Communications - Scientific Letters of the University of Zilina,* vol. 24, no. 1, pp. B49-B58, 2022.

[14] Enapter, "AEM Technology," 2024. [Online]. Available: https://handbook.enapter.com/knowledge_base/aem_technology.html#what-is-the-energy-content-of-hydrogen.

[15] HandWiki, "Standard Conditions for Temperature and Pressure," 09 Nov 2022. [Online]. Available: https://encyclopedia.pub/entry/33636#:~:text=Before%201918,%20many%20professionals%20and.