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The Role, Construction and Utilization Trends of Fuel Cells in the Propulsion of Road Vehicles

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Abstract
This scientific paper presents the authors own views on the role, construction and trends in the use of fuel cells in the propulsion of road vehicles. The paper is in the form of a literature review and is intended to help those interested to find out important facts about the principles of operation, typology, construction types and efficiency of fuel cells. Readers can also learn about the production, use and storage of hydrogen and a case study on the applications and disadvantages of fuel cells in the road vehicle industry. At the end specific conclusions of the paper are presented.

Keywords: Fuel Cell, Hydrogen, Road Vehicle, Construction, Operation, Applications

1. Introduction

The deficiencies of storing electrical energy in batteries (in the case of electrically propelled vehicles) can be overcome by generating electricity by fuel cells. The fuel cell is the viable alternative for obtaining electricity from electric storage batteries and consists of electrochemical conversion, i.e. the direct, clean and silent conversion of the chemical energy contained in a wide variety of substances into electrical energy. Unlike primary cells, commonly called "batteries", or accumulators (secondary cells), fuel cells are characterized by the fact that the reactants are constantly transported to the electrodes and the reaction products are permanently removed. The principle behind the functioning of fuel cells was discovered in 1839 by the Welsh physicist and judge Sir William Grove, who tried to reverse the process of electrolysisHe thus realized the first fuel cell which he called the *"gas voltaic battery"*. Although more than 150 years have passed since the first attestation of their principle of operation, fuel cells are still not accessible to the general public because of the high cost of their construction. Their first significant use was in 1960, when they became the main source of electricity for the Gemini space missions. From then on, and continuing with the space missions that followed, fuel cells were increasingly used and proved safer than nuclear reactors and cheaper than solar cells. Since the 1990s, the scientific and technical importance of fuel cells has become clear and they have come to the foreground of energy technologies. As high energy density sources, they have become feasible for both stationary and portable applications. For example, the US-based ONSI Corporation introduced the stationary PC25 model to the market in 1992 and has sold nearly 250 units to date.This model, which is not one of the most efficient, runs on natural gas and offers an electrical efficiency of 40% and a total efficiency (electrical and thermal) of 80%, with extremely low pollutant emissions. In the meantime, several companies have launched different types of fuel cells on the market, which have proven their efficiency in different categories of applications. Their theoretical and practical advantages have led some specialists to consider them one of the most important energy sources of the future. Their main advantages are: High efficiency, almost zero pollution, quiet operation and much higher reliability than internal combustion engines, due to fewer moving parts. The first hydrogen fuel cells were used to generate electricity in the Apollo space missions, after which numerous other applications were found. Subsequent research has led to the idea that hydrogen fuel cell vehicles could be a viable alternative. Fuel cells work by combining hydrogen and oxygen in a chemical reaction to create electricity without the need for conventional engines, which are noisy and polluting. Generally speaking, a fuel cell works like a battery. This new direction in the automotive industry has also been followed by the world's major car manufacturers. The first prototypes of fuel-cell cars produced by major companies such as General Motors, Honda, Toyota, Ford, Opel and Ford have appeared on the world market.The main drawback of this mode of vehicle propulsion is the storage of hydrogen, which can only be done in pressurized containers.

Building a distribution network for hydrogen is also a big problem. Fuel cell vehicle systems operate by local electrochemical combination of hydrogen with air from the outside environment.

2. The role of fuel cell construction and utilization trends

As has been shown, one of the alternative ways of obtaining electrical energy is electrochemical conversion, i.e. the direct, clean and silent transformation of the chemical energy contained in a wide variety of substances into the most advantageous form of energy, electrical energy. This conversion process takes place in systems and devices generically called Electrochemical Electric Power Sources or Electrochemical Fuel Cells (Figure 1). In other words the fuel cell is a galvanic cell in which the free energy of a chemical reaction is converted into electrical energy. In the case of a conventional fuel cell, which works with hydrogen and oxygen, the reaction that takes place is:

$$H_2 + \frac{1}{2} \cdot O_2 \rightarrow H_2O \quad (1)$$

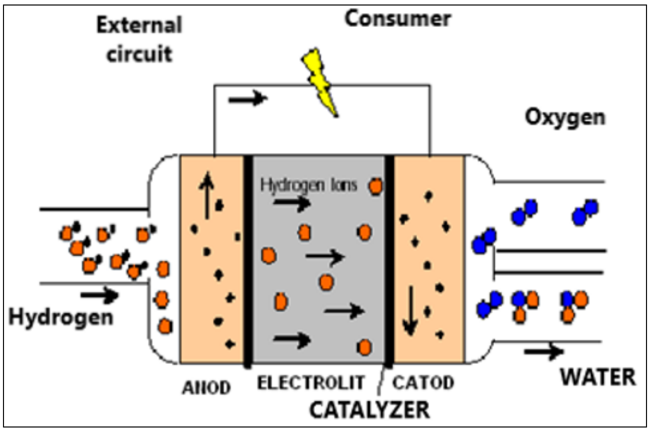

Fig 1: Schematic of how the fuel cell works [8]

All fuel cells have a similar structure: They contain two electrodes Anode and Cathode separated by an electrolyte and connected in an external circuit. The anode is fed with gaseous fuels, where direct oxidation takes place, and the cathode is fed with an oxidizer (e.g. oxygen in air). The electrodes must be permeable, so have a porous structure. The electrolyte must have as low permeability as possible. Batteries consist of a number of electric cells connected together, usually to produce a voltage (electric voltage) higher than a single electric cell.

2.1 Short history

Dead frogs led to the invention of batteries. In 1786, Italian scientist Luigi Galvani discovered that the muscles of dissected frogs contracted when he touched them with a scalpel. Then by chance he discovered that legs could be made to move just by touching them to metal. Galvani was puzzled as to the nature of this phenomenon, and its source. The answer was provided in the 1790s by the Italian scientist Alessandro Volta. The frog's legs had come into contact because the liquids inside them reacted on contact with two different metals: Brass and iron. This combination formed a simple electric battery, and the current produced by the battery made the frog's leg muscles contract. Volta then made an electric battery by putting wet paper between copper and zinc disks. This battery was extremely weak, but Volta soon devised practical cells and batteries. One of these batteries consisted of a column of electric cells made of zinc and silver plates with paper separators soaked in brine. This type of battery was called a voltaic battery. After the realization of the battery named after Volta, this source of energy was used by Nicholson and Carlisle to decompose water into hydrogen and oxygen, and by Davy in 1307 to decompose alkali. Daniell and Faraday brilliantly continued their experiments on these new energy sources in the first half of the last century. A major event in the development of electrochemical energy sources was the realization of the lead-acid battery by Plante in 1859. Nine years later, in 1868, Leclanche invented the zinc-pyrolusite battery, which quickly became one of the most popular electrochemical energy sources. The seventh decennium of our century is the decade that saw the validation of the use of fuel cells in space exploration. The objectives in developing hydrogen-oxygen (H_2-O_2) fuel cells for use in spacecraft were to create lightweight, independent power sources for multiple purposes: Command and control, communications, radar, imaging, and powering vehicles used to explore the surfaces of other planets or natural satellites.

These fuel cells must meet certain conditions such as:

- Very high reliability and maintenance, with very limited repair possibilities;
- High specific energies and powers, it is known that launching a one kilogram mass into outer space costs from a few thousand to ten thousand dollars (in 1989);
- High resistance to special conditions in outer space, conditions related to weightlessness, as well as those existing on extraterrestrial surfaces: Large fluctuations in temperature and pressure, meteorites, radiation, absence of atmosphere.

The US Gemini and Apollo space programs used 2kW H2-O2 fuel cell systems to power the space capsules.

2.2 Working principle and types of fuel cells

The idea of obtaining electrical energy by direct conversion of chemical energy arose when the problem arose of reverse electrolysis of water (which produces the components of water), i.e. obtaining electricity from the reaction between hydrogen and oxygen. In 1801, Davy achieved this by using carbon as a fuel and nitric acid as an oxidizer. The research was continued by Ostwald Nerst, Haber etc. because the direct conversion of chemical energy into electrical energy avoids the thermal energy link and hence the conversion efficiency does not depend on Carnot limits.

Fuel cells can be framed as soft energy systems due to the following characteristics:

- Produce DC electricity at low voltages and medium currents that can be used directly by end users;
- Do not pollute the environment;
- Operates quietly, without vibration or noise, no moving parts.

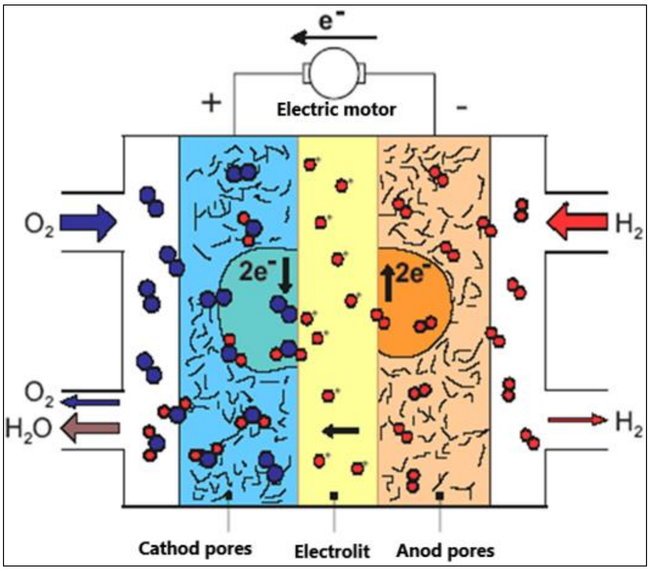

Fig 2: Schematic of a hydrogen fuel cell [9]

In principle, the energy released in the oxidation of conventional fuels, generally used in the form of heat, can be converted directly into electrical energy with excellent efficiency in a fuel cell. Since in almost all oxidation reactions there is a transfer of electrons between the fuel and the oxidizer, it is obvious that the chemical energy of oxidation can be converted directly into electrical energy. An oxidation-reduction reaction occurs in which oxidation of the fuel and reduction of the oxidizer take place with a loss of one and a gain of electrons for the other. Any galvanic element involves oxidation at the negative pole (loss of electrons) and reduction at the positive pole (gain of electrons) and, as with all galvanic elements, fuel cells tend to separate the two partial reactions in the sense that the exchanged electrons pass through an external utilization circuit.

To ensure this process takes place, it is essential to realize an element containing an anode, a cathode and an electrolyte that can be directly supplied with a fuel and air (Figure 2). The oxygen required to burn the fuel is ionized at the cathode; the ions then migrate into the electrolyte to arrive at the anode where oxidation of the fuel takes place.

How a fuel cell works will be explained below, using as an example the simplest fuel cell that works with hydrogen and oxygen, the **hydrogen-oxygen fuel cell.**

The irreversible kinetic processes associated with a fuel cell consist of a series of oxidation-reduction reactions. A fuel A is transported to the porous anode where it is absorbed on its surface, then dissociated into ions and electrons in an oxidation process. After that, the migration of electrons from the anode and the release of ionic gas at the anode surface takes place. In the electrolyte, the transport of AZ+ ions from the anode to the cathode must be ensured against the resulting electric charge on account of the electrochemical impressed field. At the cathode, ions (arriving via the electrolyte), electrons (arriving via the external circuit) and oxidant B meet. The reduction reaction takes place, resulting in the reaction product to be eliminated. The fuel cell therefore consists of three elements: The electrolyte, the electrodes and the reactants (a fuel and an oxidant).

A fuel cell uses hydrogen as fuel, oxygen as oxidant, alkaline electrolyte and electrodes that also act as catalysts. During operation, the electrodes do not undergo any structural change, but only serve as a support for the reaction; catalytic oxidation of atomic hydrogen takes place at the anode and catalytic reduction of atomic oxygen at the cathode. Catalytic oxidation and reduction take place in a three-phase (gas-liquid-solid) regime at the surface of the catalyst according to the global reaction:

$$H_2 + \frac{1}{2}O_2 = H_2O \qquad (2)$$

2.3 Construction types of fuel cells

Electrochemical energy sources are classified by the type of electrode reaction, namely:

a) If the reaction is irreversible, electricity is produced from a limited amount of reactants and their regeneration by electrolysis is not possible, the source is called the *primary cell*;
b) If the reaction is reversible and the reactants consumed during the production of electricity can be regenerated by electrolysis, the source is called a *secondary battery* or *accumulator*;
c) Where reactants are transported all the time to the electrodes and reaction products are removed simultaneously the source becomes a so-called *fuel cell*.

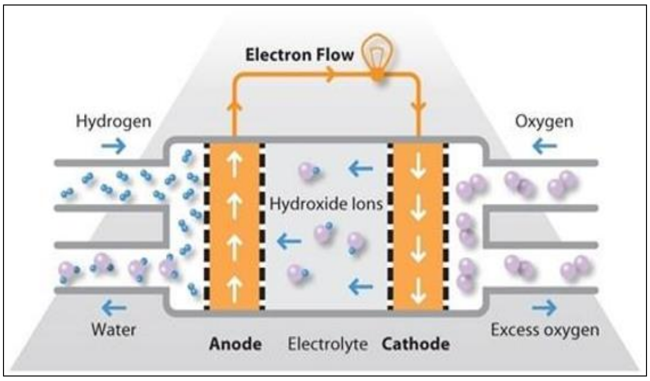

Fig 3: Alkaline fuel cell (AFC) [11]

Fuel cells are usually categorized by the type of electrolyte used, the electrolyte being the substance between the two electrodes that allows the hydrogen ions to move between the two electrodes.

Although there are several dozen types of fuel cells, six types are currently in use or under development. Although there are constructional differences between these fuel cell designs, the main distinguishing feature is the type of electrolyte.

These constructive types are:

A. Alkaline Hydride Fuel Cell (AFC) (Figure 3), was the first type of fuel cell to be used in space programs. AFC uses potassium hydroxide (KOH) as the electrolyte, and operates at temperatures in the range of 100-250º C. AFC cells operating at higher temperatures use an electrolyte with a higher concentration of about 85% while those operating at lower temperatures contain a more dilute electrolyte with a concentration of 35-50%. The electrolyte is retained in an asbestos support, which bonds to the electrodes. This fuel cell uses pure hydrogen as fuel, as contact with other substances such as carbon monoxide or carbon dioxide will destroy the cell.

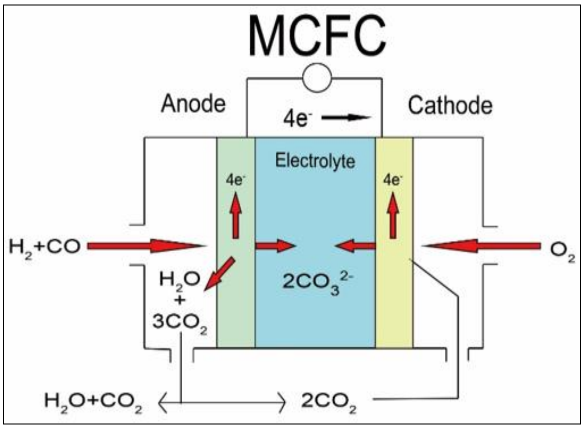

Fig 4: MCFC fuel cell [10]

B. Molten carbonate fuel cells (MCFC) (Figure 4), are currently used in power plants to produce electricity. Alkaline carbonates (Sodium, Potassium, Lithium based salts, Na_2CO_3, K_2CO_2 or Li_2CO_3) or combinations of alkaline carbonates that are deposited on a ceramic structure of Lithium Aluminum Oxide ($LiAlO_2$) can be used as electrolyte in such a fuel cell. Such a battery operates at temperatures of 600-700ºC, at which temperatures the alkaline carbonates melt resulting in a molten salt with very good conductive properties. Nickel and Nickel Oxide (NiO) are used for the construction of the electrodes. The high temperatures at which these fuel cells operate mean that when energy recuperators are used, the thermal efficiency of the system can reach 85%.

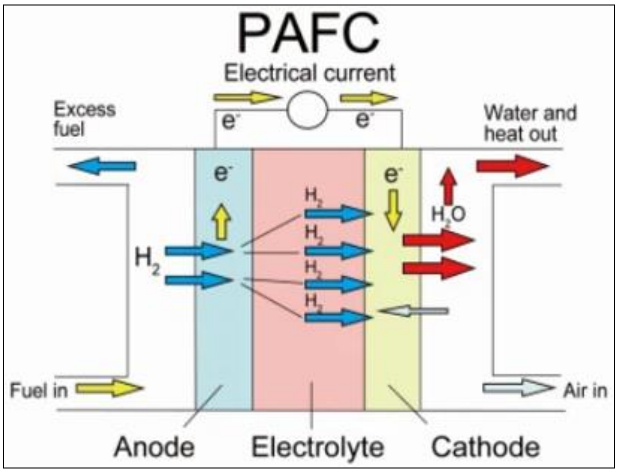

Fig 5: PAFC fuel cell [12]

C. Phosphoric acid fuel cell (PAFC) (Figure 5), is the most well developed of all types of fuel cells, it is the basis of the first fuel cells that were commercialized. As electrolyte this cell uses 100% phosphoric acid (H3PO4), and operates at temperatures of 150-220o C. Phosphoric acid at this concentration has a high stability, which allows operation at these temperatures. At lower temperatures there are problems of contamination of the catalyst, generally platinum with CO, and ion conductivity through the electrolyte decreases. Operating at temperatures up to 200o C, current generators based on this type of battery are also used to heat water for domestic use.

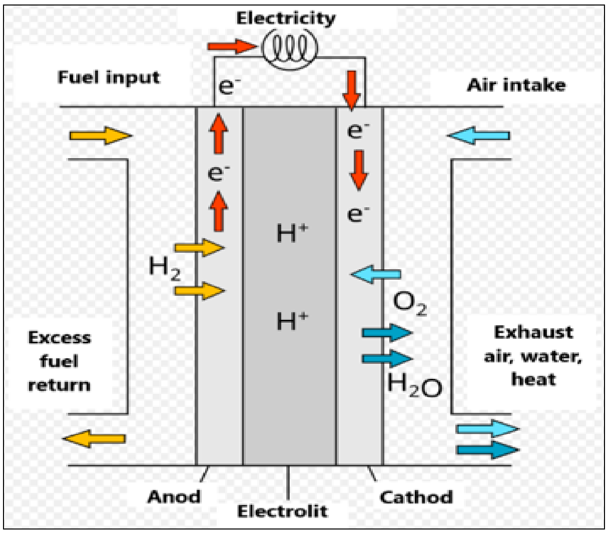

Fig 6: PEMFC fuel cell [13]

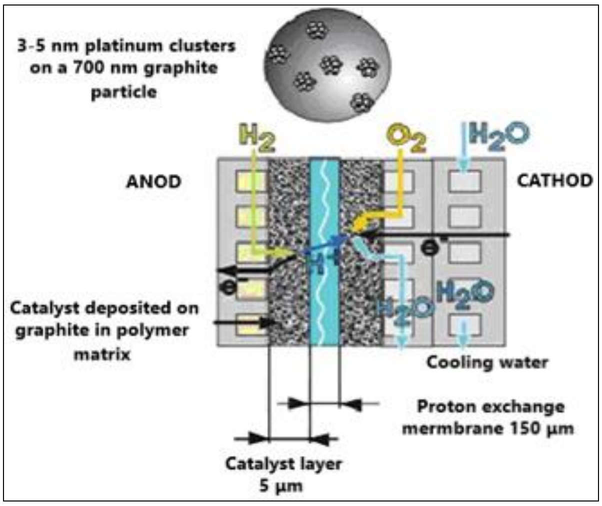

Fig 7: An advanced version of a PEM cell assembly with deposited catalyst

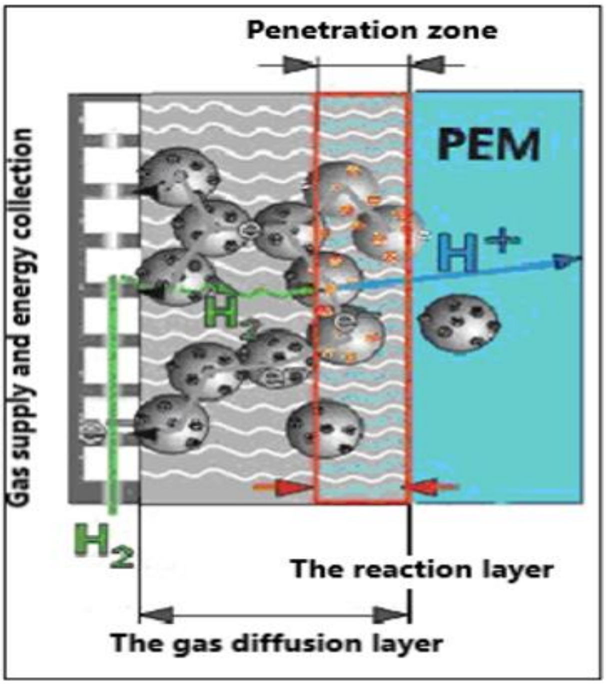

Fig 8: A Membrane Electrode Assembly (MEA) model using CCM

D. Proton exchange membrane fuel cell (PEMFC) (Figure 6), contains an electrolyte which is a solid layer of polymer (sulphuric acid) that allows the transfer of protons from one side of the electrolyte to the other. The fuels required for PEMFCs are hydrogen and oxide, although ambient air can also be used as an oxidizer. It operates at low temperatures around 90oC limited by the thermal properties of the membrane. About 30 years ago, Dupont developed a copolymer of perfluorosulfonic acid and PTFE in acid form, known as Nafion. DuPont's Nafion membranes are films based on the Nafion PFSA polymer. Nafion PFSA membranes are widely used in proton exchange membrane (PEM) fuel cells. The membrane functions as a separator and solid electrolyte in a variety of electrochemical cells that require selective cation transport across the cell junction. The polymer is chemically resistant and durable. The use of a solid polymer eliminates the need for an airtight compartment for the liquid electrolyte as well as corrosion and related safety issues (Figure 7). The catalyst, usually platinum, is deposited as nano clusters (3 - 5nm) on a graphite support - graphite particles of 0.7 - 1 μm and embedded on one side in a graphitized paper foil. Two foils are applied on both sides of the membrane forming the anode and cathode catalyst layers. This PEM assembly is known as a catalyst deposited membrane (CCM). The graphitized paper can be completely removed if a thicker layer of catalyst (5μm) is deposited to form an electrically conductive layer on the membrane, with a decrease in the performance of the platinum catalyst. Figure 8 shows a model of a Membrane Electrode Assembly (MEA) using CCM. The gas supply and electron collection is through a gas conducting profiled plate that forms the outer boundary of a cell. The gas is fed laterally through the electrode edges to the inside of the electrode, while the electrons are transported by the electroconductive plate to the next cell. At higher power densities an additional electroconductive plate with a cooling water channel system is introduced between each two adjacent cells. The Nafion-based proton exchange membrane typically operates below 70-85°C. The low operating temperature ensures fast start-up and does not require thermal insulation for personnel protection. Approximately 50% of maximum power is immediately available at room temperature. Full power is reached in about 3 minutes under normal conditions. Recent breakthroughs in design and performance offer the possibility to lower the cost of PEM fuel cells below the cost of any other fuel cell.

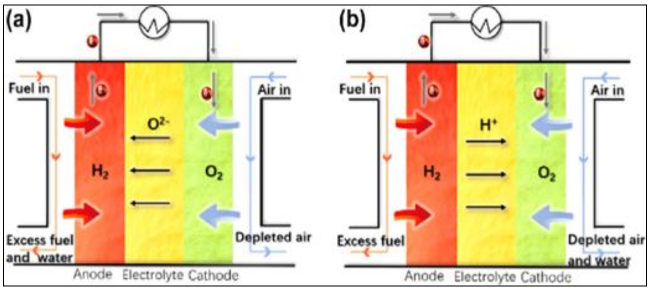

Fig 9: Solid Oxide Fuel Cells (SOFC) [14]

E. Solid Oxide Fuel Cells (SOFC) (Figure 9), are used in the construction of power generators with power ratings between 1kW and 250 kW. SOFC uses as electrolyte a neporous metal oxide (Y_2O_3 - stabilized ZrO_2), and operates at temperatures of 650-1000ºC, where the ion conduction is achieved by Oxygen ions. SOFC cells offer high stability and reliability characteristic of solid ceramic constructions. The high temperatures of around 1000ºC allow great flexibility in terms of the fuels used, and can have high performance when used in applications that are based on combined cycles. SOFCs approach 60% efficiency in converting chemical energy to electricity and can reach 85%, total thermal efficiency.

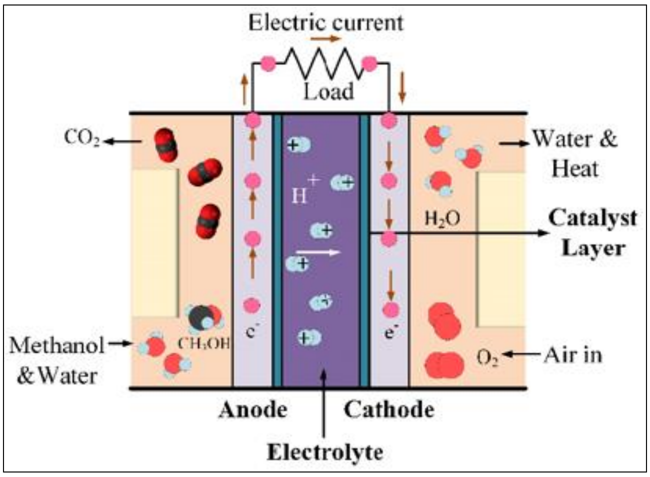

Fig 10: Methanol fuel cell (DMFC) [15]

F. Methanol fuel cell (DMFC) (Figure 10), is similar in construction to PEMFC. However at the anode the DMFC has a catalyst that attracts hydrogen from liquid methanol, thus eliminating the need for a fuel reformer, and thus solving the problem of hydrogen transport and storage. Although a very attractive solution, its low efficiency prevents it from becoming a commercial application. The methanol fuel cell (DFMC) is the only fuel cell that does not use hydrogen but methanol. This type of cell requires no reformers because the cell itself converts methanol into hydrogen protons, free electrons and carbon monoxide. As it does not require reformers, DFMC is the most suitable cell for use in cars as a very simple energy source. So one solution is to use fuel cells that use hydrocarbons, which are hydrogen carriers. In this way it is possible, with minor modifications, to use the existing distribution network and obtain high-performance vehicles whose energy source is no longer limited by the efficiencies imposed by the Carnot cycle. Among the companies producing such vehicles we can mention General Motors, Toyota, VW, Renault, which have developed a gasoline-based fuel processor for use in fuel cell vehicles with fuel cell technology. Unfortunately, the main drawback of this propulsion system is the non-renewability of fossil fuels. The development of ethanol fuel cells, however, promises to solve the problem of vehicle propulsion as well as obtaining electricity from renewable resources. Ethanol obtained from the processing of plant matter or waste is a renewable source of energy, including the instantaneous production of hydrogen. Fuel cells convert this energy carrier into electricity at maximum efficiency, much more cost-effectively than internal combustion engines.

The major advantage of using ethanol is its compatibility with gasoline reforming technology and its flexibility to be used neat or in a gasoline/ethanol mixture. In the case of ethanol fuel cells, a fuel processor has been developed that enables fuel cell plants to run on ethanol. Ethanol used for transportation applications reduces dependence on oil, reduces air pollution and up to 40-50% efficiency in converting fuel into usable energy can be achieved. In fuel cells, hydrated ethanol (alcohol with reduced water content) can be used without any efficiency loss compared to 100% ethanol.

The following electrochemical reactions take place in fuel cells:

- At the anode: A first-order reaction

$$C_2H_5OH + 2OH^- \rightarrow CH_3CHO + 2H_2O + 2e^- \tag{3}$$

- at the cathod:

$$4e^- + O_2 + 2H_2O \rightarrow 4OH^- \tag{4}$$

Table 1 shows the main fuel cells and their characteristics.

Table 1: Main fuel cells and their characteristics

	AFC	**PEMFC**	**DMFC**	**PAFC**	**MCFC**	**SOFC**
Operating temperature (°C)	100-250	60-120	60-120	150-220	600-800	800-1000
Anode reactions	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$	$H_2 \rightarrow 2H^+ + 2e^-$	$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$
Cathode reactions	$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$	$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$\frac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$	$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$	$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$
Applications	Transport Space program Military Energy storage systems			Electricity and heat production in decentralized stationary energy systems	Production of electricity and heat in decentralized stationary energy systems and transport (trains, ships, etc)	
Power output	Small installations 5-150kW Modular construction	Small installations 5-250kW Modular construction	Small installations 5kW	Small-medium installations 50kW-11MW	Small installations 100kW-2MW	Small installations 100-250kW
The charge carrier in electrolyte	OH^-	H^+	H^+	H^+	CO_3^{2-}	O^{2-}

2.4 Fuel cell efficiency

The basic reaction in a fuel cell is the oxidation of a fuel, just as in conventional primary fuel cells the oxidation of a metal takes place. The efficiency of fuel cells is superior to turbogenerators in today's power plants because the reaction enthalpy is converted directly into electrical energy, except for an entropic term. In order to compare the fuel cell with other energy production systems, such as the internal combustion engine, an assessment of the efficiency of the system is necessary.

For the internal combustion engine, the maximum efficiency is expressed by the Carnot cycle efficiency:

$$\eta_C = 1 - \frac{T_1}{T_2} \tag{5}$$

Where, T1 and T2 are two absolute temperatures in thermal engine operation. For the fuel cell, the maximum efficiency is expressed by the variation of Gibbs free energy (ΔG) and the variation of enthalpy (ΔH) in the electrochemical reaction:

$$\eta_{PC} = \frac{\Delta G}{\Delta H} \tag{6}$$

The overall electrical conversion efficiency of a fuel cell is higher than that of thermal engine systems. A comparison of overall electrical conversion efficiencies is shown in Figure 11.

The theoretical value of the isothermal efficiency (η_{iz}) is higher than the Carnot cycle:

$$\eta_{iz} = W_{max}/\Delta H = \Delta G/\Delta H = 1 - T\Delta S/\Delta H; \tag{7}$$

Where, W_{max} is the maximum electrical energy.

The isothermal efficiency of the reactions taking place in fuel cells can reach and theoretically exceed 80%. The electrical efficiency (η_{el}) of fuel cells is obtained by relating the electrical energy obtained (W_{el}) to the enthalpy of reaction:

$$\eta_{el} = W_{el}/\Delta H = W_{el}/W_{max} = E/E_{max}\, \eta_{iz}; \tag{8}$$

Where, E is the electromotive voltage in the load.

E_{max} is the corresponding Emax and the stresses in the situation when the water resulting from the reaction is in liquid or gaseous form. The isothermal efficiency of fuel cells depends, as can be seen from relation 8, on the size of the reaction entropy which, when positive, implies higher efficiencies than unity, because some of the heat of the environment is taken up. This phenomenon is encountered in experimental situations and is of no practical interest. Very high theoretical efficiencies can be observed for the rest of the reactors, far exceeding the theoretical Carnot cycle efficiency of 30-50%. However, in practice, due to the internal polarization of the stack, voltage drops, etc., efficiencies of 50-60% are obtained which are quite high compared to other practical conversion procedures.

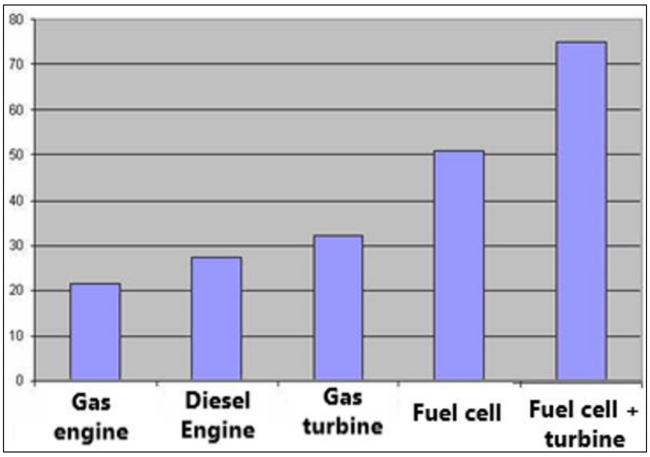

Fig 11: Comparison between the electrical conversion efficiency of fuel cells and other energy conversion systems [16]

Analysis of the data presented in Figure 11 shows that internal combustion engines lose thermal energy through cooling (absolutely necessary for engine integrity) and through the exhaust system. Therefore they have the lowest efficiency. Their efficiency is in the [20-30]% range. Fuel cells are not subject to the same constraints. Their operating temperature is much lower than that developed in the combustion chambers of a heat engine, the temperature is more easily compensated by the cooling system and nothing is lost through the exhaust system. The result is that, at the same effective power, the fuel cell system loses twice as much thermal energy through the cooling radiator as the internal combustion engine. This explains the superior fuel cell efficiency of over 70%.

2.5 Producing and using hydrogen

It is estimated that hydrogen accounts for more than 90% of the total number of atoms, or three-fourths of the entire mass of the universe. This element is present in stars and plays an important role in energizing the universe. Pure hydrogen is a gas that is found to a very small extent in the universe. On Earth, it is found mainly in chemical combinations with oxygen to form water, but also in organic matter such as plants, oil, coal, etc. It has been established that under normal conditions hydrogen gas is a mixture of two types of molecules, known as ortho and para, which differ from each other in the backbones of electrons and nuclei. Normal hydrogen, H, at room temperature contains 25% of the para form and 75% of the ortho form. The ortho form cannot be prepared in its pure state. As the two forms differ energetically they also differ in their physical properties. The melting and boiling points for para hydrogen are 0.1°C lower than for normal hydrogen, H. Hydrogen production is nothing new. Currently, the annual worldwide production of hydrogen that is produced, stored, transported and used is 500 billion m^3. This is mainly produced in the chemical (petrochemical) industry. Hydrogen can be produced from abundant domestic resources including natural gas, coal, biomass and even water. Japan's Ministry of Economy, Industry and Trade has asked the Natural Resources and Energy Agency to use coke oven gas from steel production as a primary source for hydrogen production.

Hydrogen can be obtained by the following methods:

- Injecting water vapor into the mass of glowing coal;
- Water electrolysis;
- Thermal cracking of certain hydrocarbons;
- Chemical reaction either between sodium or potassium hydroxide and aluminum or between certain metals and certain acids;
- Biogas obtained from the decomposition of waste - by thermolysis.

Table 2 shows the properties of hydrogen reforming methods.

Table 2: Properties of hydrogen reforming methods

	Diesel	Gasoline	Hydrogen (gases)	Hydrogen (liquid)	Methanol	Natural gas
Safety	medium	medium	medium	high	high	medium
Ease of manufacturing	very hard	hard	is not necessary	is not necessary	easy	medium
Resources	high	very high	limited	very limited	medium	high
Existing infrastructure	very good	very good	putina	little	little	very good
Pollution	high	high	very little	medium	medium	medium

The aim of reforming plants is to obtain as much hydrogen as possible from the fuel molecules under conditions of minimal carbon monoxide (CO) emissions. The molecular formula of methanol is CH_3OH. The process of obtaining hydrogen by reforming matanol starts by vaporizing liquid methanol and water. The mixture of these two gases is introduced into a heated chamber containing a catalyst. The relationships that lead to hydrogen are:

$$CH_3OH \Rightarrow CO + 2H_2 \qquad (9)$$

$$H_2O + CO \Rightarrow CO_2 + H_2 \qquad (10)$$

None of these reactions is perfect, which is why at the end of the process there are also quantities of methanol, natural gas and carbon monoxide that did not participate in the reaction. These substances are burned in the presence of another catalyst and a reduced amount of oxygen to support the combustion process, thus converting the remaining carbon monoxide into carbon dioxide. It is very important to eliminate carbon monoxide, because it pollutes and at the same time reduces the life of the combustion cells.

The process of obtaining hydrogen by reforming natural gas is similar to that of methanol, natural gas having methane (CH_4) as its main component. The relationships that lead to hydrogen are:

$$CH_4 + H_2O \Rightarrow CO + 3H_2 \qquad (11)$$

$$H_2O + CO \Rightarrow CO_2 + H_2 \qquad (12)$$

Direct thermal water splitting and water splitting using light quanta are unconventional methods of obtaining hydrogen. Using light energy for water dissociation is possible because water vapor absorbs light and ultraviolet radiation photons. Under these conditions the H-OH bond is broken with a hydrogen formation efficiency of approx. 0,4 %.

"Solar hydrogen" has real potential to become more cost-effective as an energy source than the energy provided by atomic power plants.

Hydrogen can be produced either in stationary electrolysis or catalytic reforming plants for methanol, which also requires a hydrogen distribution network, or in on-board plants (catalytic reforming of a hydrocarbon on board a vehicle). Hydrogen is the only element whose isotopes have different names. Hydrogen's ordinary isotope, H, is known as Protium, two other isotopes are Deuterium (one proton and one neutron) and Tritium (one proton and two neutrons). Deuterium and tritium are used as fuel in nuclear fusion reactors. Deuterium is used as a neutron moderator and tritium as a radioactive agent in the production of luminous dyes and as a tracer. Tritium is prepared in nuclear reactors and used in the production of hydrogen bombs. Large quantities of hydrogen are needed in the dehydrogenation network for fixing nitrogen from the air in the Haber ammonia process and for hydrogenating fats or oils. Hydrogen is also used in large quantities in the production of methanol, in hydrocracking and in hydrodesulphurization. Other uses of hydrogen are in the health field, in the preparation of rocket fuel, in welding, in the production of hydrochloric acid, and in the reduction of ores Liquid hydrogen is used in cryogenics, and in the study of superconductivity. Metallic hydrogen is metastable and it is predicted that it could be a superconductor at room temperature. According to the International Energy Agency (IEA), manufactured hydrogen uses 2% of the world's energy consumption, or about 170 million tons of oil equivalent per year (toe): 50% of the hydrogen produced is used in the manufacture of fertilizers; 37% is used in the petrochemical industry and 13% in the chemical industry. At this date, taking into account the industrial manufacturing process, 48% of the world's hydrogen is obtained from natural gas by catalytic reforming [1], 30% from various oil fractions, 18% from coal, by gasification [2, p. 4], [3]. But according to some researchers, the principal source of hydrogen remains fossil fuels [2]. The reaction to make hydrogen produces carbon dioxide. This leads to the same situation as with electric cars: We don't pollute when we use them, but we pollute when we manufacture them. That leaves 4% of the total hydrogen produced that could be environmentally friendly: The industrial manufacturing process of water electrolysis [4, p. 189; 202]. Water is enough. Green" hydrogen can also be made from renewable energy or biomass [5]. But electrolysis requires electricity. If it doesn't come from renewable sources, we are back to the problem of environmental pollution.

Hydrogen fuel cells are a potential source of power compatible with renewable energy sources. Wind-based electrolysis currently appears to be the cheapest and most promising source of renewable energy through hydrogen production. New wind generators are capable of producing large amounts of energy. When there is no wind, the stored hydrogen provides a great medium for stored energy and allows electricity to be generated continuously.

2.6 Hydrogen storage

Hydrogen gas can be stored at high pressure. Tanks for pressurized gas storage have a construction that differs depending on the type of application that determines the required pressure level. For the vast majority of stationary tanks the pressure is relatively low (about 350 bar). The requirements for applications involving mobile tanks differ substantially, with the tank pressure in these applications reaching up to 700 bar. The pressure tanks are made of steel and this solution is applied for almost all hydrogen tanks used in existing vehicles. But these tanks are expensive, cumbersome and heavy (over 90% of the mass of the full tank).Modern pressure tanks are made of composite materials (carbon fiber composites with a fine internal metal structure).

Another possibility for storing hydrogen is the use of metal hydrides composed of metals and hydrogen, which, under certain conditions of temperature (between 150 and 300º C) and pressure, can release hydrogen molecules. This storage technology uses certain metal alloys that absorb hydrogen like a sponge. The metal forms metal hydrides by absorbing hydrogen. In terms of volume, metal hydrides have a very high storage capacity but being a very heavy storage medium it is not recommended for use in mobile applications. In addition metal hydrides are very expensive due to the high price of the materials. It is also possible to store hydrogen in liquid form. This storage method can be applied, with high energy consumption, to cool hydrogen to -253º C. The cryogenic tanks manufactured today are of very high quality. The losses resulting from the gradual heating of the liquid hydrogen in the tank (loss of hydrogen vapors) can be kept within low limits. Liquid storage is recommended for mobile applications because the storage space of liquid gas tanks is the smallest. Automated robots are already available for refilling these tanks. Liquid hydrogen storage in stationary tanks is only applicable when the hydrogen needs to be in this state, e.g. in hydrogen refueling stations.

If large quantities of hydrogen need to be stored in the future economy, it could be stored at a pressure of about 50 bar in underground natural caverns. Natural gas is stored in such caverns in France, the USA and Germany, and it is assumed that this method could also be applied to hydrogen storage in the future.

2.7 Fuel cell applications in the automotive industry. Case study

Today, the hydrogen fuel cell is used in several fields of application, among which we will mention here: Automotive engines. As the fuel cell converts fuel directly into electricity, it is by definition a hybrid-electric vehicle technology. The fuel-to-energy conversion efficiency is expected to be around 50% in the field of automotive engines. Currently, however, fuel cells are very expensive because they are not mass-produced and the infrastructure for refueling hydrogen vehicles is not yet widespread. A fuel cell powered car can run its own supply of hydrogen in a pressurized tank, or it can generate its own hydrogen as needed in a chemical reactor called a reformer.

The U.S. Department of Energy (DOE), in collaboration with Ford, has developed a zero-emission fuel cell-based vehicle drive system. The aim of these joint activities was to test a complete fuel cell vehicle propulsion system in the laboratory. In this project work is continuing to assess the risk of using hydrogen as a fuel, the operational safety of fuel cell energy and to verify the integration of power generation with hydrogen vehicle refueling system. The world's first 50 kW fuel cell power system was built in 1999 by International Fuel Cells in a DOE collaboration with Ford. The system provided enough energy to power a medium-sized car, weighing about 140 kg and with a volume of 250 cm3 that allowed it to be placed under the vehicle's hood. The hydrogen engine was equipped with nickel-cadmium batteries that offer the best performance in terms of environmental protection and energy storage capacity per unit volume. The nickel-cadmium battery is made up of three separate well-protected cells, and the vehicle will be able to continue to run if one of the three cells malfunctions. In the electric scheme, the battery is located between the fuel cell, which converts hydrogen into electricity, and the electric drive motors located in the four wheels. A design feature of the hydrogen-powered vehicle is the integration of the fuel cell with the technology of systemic electronization of vehicle and engine operation, which will replace the previous predominantly mechanical systems of steering control, braking, acceleration, securing the vehicle's movement, etc. This replacement will free up space in the engine and transmission compartment because electronic systems are much more compact than mechanical ones. The performance of electronic systems can be programmed by software.

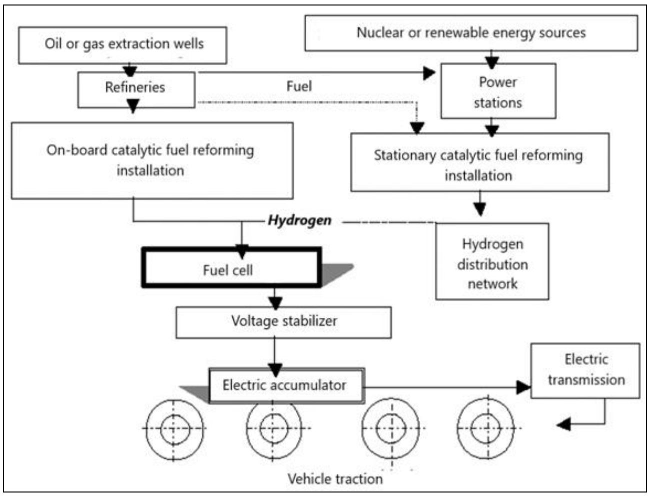

Fig 12: Schematic of hydrogen production and utilization in hybrid fuel cell vehicles

In addition, in the absence of conventional engine-to-wheel power transmission systems, the chassis structure can be modified, allowing body designers to create aerodynamic shapes that differ essentially from conventional ones, thus satisfying consumer requirements. Figure 12 shows a schematic of hydrogen production and utilization in hybrid fuel cell vehicles. General Motors, recognizing these new opportunities, exhibited a new concept car called Autonomy at the Paris Motor Show in September 2002 (Figure 13). A fully developed Autonomy car, with integrated electronic control technology, is a vehicle built from the wheels up. The chassis is a thin plate on which are arranged the fuel cell battery, the hydrogen tanks, the central unit for electronic control, the heat exchangers, the steering linkage, the braking system. n Europe, Mercedes has announced that it has spent more than 20 million euro on the hydrogen pipeline, filing no fewer than 200 patents.

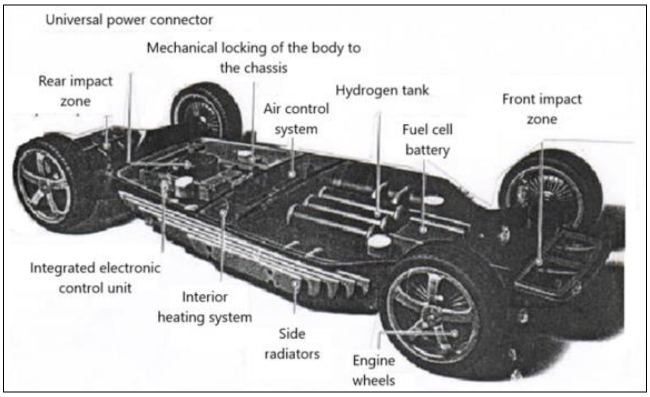

Fig 13: The Autonomy model

Fuel cell technology has advanced significantly in the last few years, with car manufacturers such as Daimler-Benz, Honda, GM, Mitsubishi, Toyota, Peugeot etc. exhibiting prototypes of fuel cell powered vehicles. Many of these prototypes were cumbersome, requiring powerful fuel cell power units, which led some observers to predict that it could be another 10-15 years before the fuel cell became economical. The September 2003 issue of "The Hydrogen & Fuel Cell Letter" published a photograph of a 1,800 hp diesel-electric locomotive converted to a fuel cell-powered version by the Fuel Cell Propulsion Institute in Denver (USA) as part of a 5-year project. Another example of a fuel cell-powered car is the Mitsubishi, featured in "The Hydrogen & Fuel Cell Letter" in October 2003.

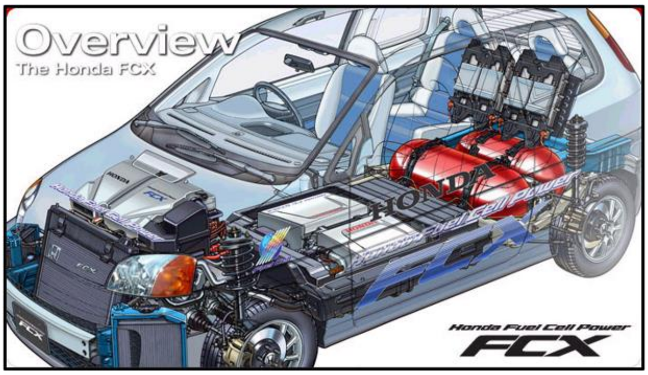

Fig 14: The Honda FCX car 2008

Honda has presented the Honda FCX model, which is one of the company's biggest achievements in hydrogen fuel cell-powered vehicles since 2008. The car is propelled electrically by an engine that is powered by the energy produced by hydrogen-fueled fuel cells (Figure 14). Taking into account important factors such as: The efficiency of electricity production, the mass of the entire system, the range and the power developed, Honda equipped the FCX with a system that combines fuel cells and high-performance batteries. This new model, which is more efficient than its predecessors, uses hydrogen fuel cells as its main power source, and batteries as an additional energy system, used when more power is needed (for overtaking), resulting in a system that is highly efficient and responsive. In order to provide sufficient space Honda has chosen to use high-pressure hydrogen tanks for this model, capable of storing enough hydrogen to give the model a reasonable range. So the Honda FCX Clarity was the first hydrogen-powered electric model to be developed in series production. The Honda FCX Clarity was produced in Japan and was available exclusively on lease for 600 dollars a month in Europe, the United States and, of course, in the homeland. With a 136-horsepower electric motor, the FCX Clarity had an official range of 450 kilometers, calculated based on the U.S. EPA standard, a tougher one compared to the old European NEDC (New European Driving Cycle) standard, replaced for all cars as of September 2017 and for all light commercial vehicles as of September 2018, with the WLTP (Worldwide Harmonized Light-Duty Vehicles Test Procedure).

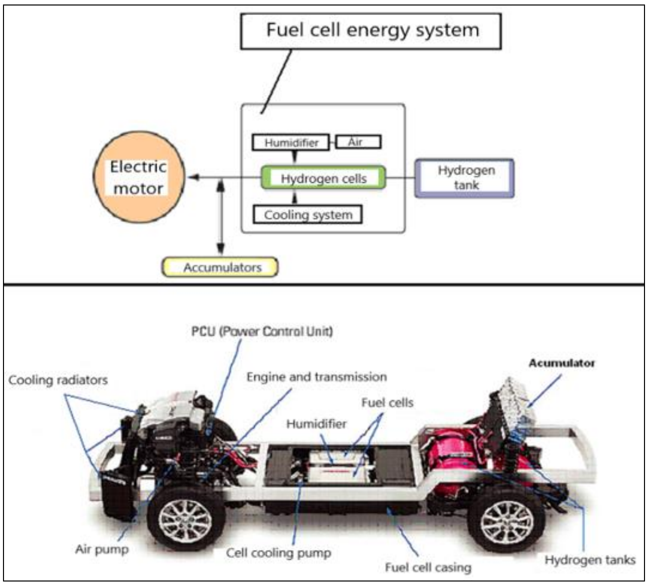

Fig 15: Main components of the fuel cell system

The Japanese automaker then played the diversification card, as around 2016 it launched both an upgraded version called the Honda Clarity Fuel Cell, as well as a battery-powered and a plug-in hybrid version. The new Clarity Fuel Cell boasted a 589-kilometer range at the time, but in the United States it could be purchased for nearly 60,000 USD or leased from just 12 California dealers.

Meanwhile, the Hyunday ix35 Fuel Cell had timidly appeared on the market. Based on the classic Tucson, the model also had a 136-horsepower engine and promised a range of 600 kilometers, based on the European NEDC standard. The recipe for failure was similar: It was sold only on lease for 600 USD a month, only in Europe, Japan, California and Toronto, and only until 2018.

The main components of the fuel cell propulsion system are:

- The PEMFC (Proton Exchange Membrane Fuel Cell) hydrogen fuel cells form two units that together develop 86kW;
- The humidifier allows the transit of the protons from the anode to the cathode, which in the case of these fuel cells is provided at the membrane level by the connection provided by the water in the membrane. To avoid water evaporation and membrane drying, the air in the fuel cell must be humidified;
- The PCU (Power Control Unit) controls electrical systems;
- The cooling system consists of three radiators, a larger front one for cooling the fuel cells and two smaller ones used to cool the powertrain (engine and transmission);
- The powertrain consists of an engine and transmission which together develop a power output of 80 kW and a torque of 272 Nm at the wheel;
- The two hydrogen tanks can be filled with 156.6 liters of hydrogen at a pressure of 350 atmospheres;
- Accumulators store energy during braking by acting as energy recuperators, which they then release to the engine under hard acceleration or when starting.

The distribution of the tractive power of the hydrogen fuel cell propulsion system is as shown in Figures 16, 17 and 18:

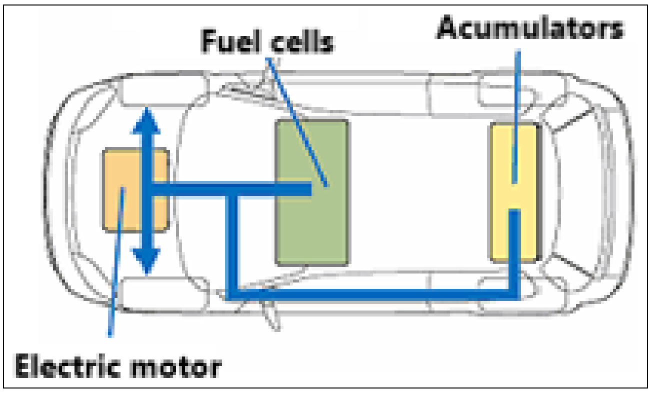

Fig 16: Starting and accelerating

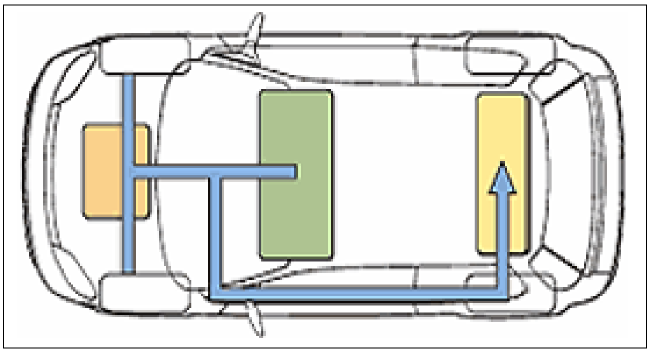

Fig 17: Braking

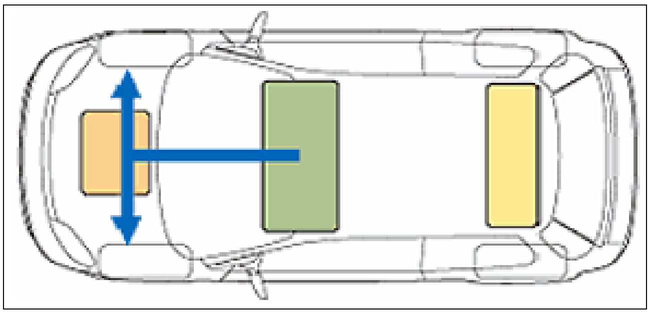

Fig 18: Smooth acceleration or running at constant speed

Table 3: Technical specifications Honda FCX

Number of passengers		4
Engine	Max. Power	95kW
	Max. Moment	256N-m
Fuel cell	Tip	PEFC(proton exchange membrane fuel cell, Honda Mfg.)
	Power	100kW
Fuel	Tip	Compressed Hydrogen
	Hydrogen storage	Pressure tanks (350 atm)
	Capacity	171 liters
Dimensions (L × W × H)		4,760 × 1,865 × 1,445mm
Speed max.		160km/h (100 mph)
Acumulators		Litiu Ion
Autonomy		270 miles

Volkswagen Research has developed a new type of High Temperature Fuel Cell (HTFC), unique in the world at that time (2011). The new system eliminates the many disadvantages of the already known Low Temperature Fuel Cell (LTFC). A high-temperature resistant membrane and specially designed electrodes for this membrane will enable more compact, more efficient and cheaper fuel cell systems. The final development of this type of propulsion is therefore getting closer. However, many manufacturers' forecasts of when hydrogen fuel cells will be ready for series production and widely available for mainstream applications have been repeatedly delayed, due to stagnant research. But Volkswagen has insisted on it, and the project has evolved significantly over the past few years. In 1999, the German carmaker began research into a membrane resistant to high temperatures. Two years later, the decision was made to work on the development of high-temperature fuel cells, starting from the basic high-temperature membrane aspect. In 2003 Volkswagen specialists achieved notable success in realizing new membranes. But electrodes adapted to this application regime had not yet been realized. In the autumn of 2006, the electrode problem was solved. The results are promising. The high-temperature fuel cell concept is currently being tested at the Volkswagen Technology Center in Isenbuttel, which is mainly dedicated to research into alternative propulsion systems and is located close to Volkswagen's general administrative center in Wolfsburg. The future sounds promising. In 2010, it is hoped that other new, higher-performance, high-temperature fuel-cell systems were in the final stages of refinement and equipped the first experimental vehicles, the precursors to industrializing this type of propulsion. The low-temperature fuel cell system has drawbacks. The membrane has to withstand temperatures around 80º C. If the temperature were to exceed this level, first the performance of the fuel cell would drop and then irreparable damage would occur. This is why experimental vehicles based on LTFC technology, in order to be able to offer similar performance to conventional cars with internal combustion engines, must be equipped with sophisticated cooling systems, which would also be high priced.

In addition, in an LTFC vehicle, the hydrogen gas and air supply system must be maintained at certain humidity levels. Otherwise, the optimum energy level cannot be reached, the fuel cell suffers permanent damage, and the electric motor can no longer operate at the parameters initially set. The humidification system takes up space, adds extra weight to the vehicle and costs extra money. That is why the new HTFC system with high-temperature fuel cells is considered so important. The membrane can withstand high temperatures, and together with the new type of electrodes, it can operate without problems at temperatures of around 160ºC. The result is similar power to that offered by the systems already known today. For vehicles equipped with HTFC systems, a current system temperature of around 120ºC is expected. In addition, humidification is no longer necessary. The cooling and water management system can be greatly simplified, resulting in less space taken up in the vehicle, lower vehicle mass and reduced costs.

In the low temperature fuel cells designed and used to date, the transit of protons from the anode to the cathode is provided at the membrane by the connection provided by the water in the membrane. To avoid water evaporation and membrane drying, the air in the fuel cell must be humidified. This has two important disadvantages. First, the membrane is not allowed to reach temperatures higher than 80ºC. This results in the need for a relatively large temperature difference between the coolant and the ambient air. For this reason, system efficiency suffers seriously. To achieve sufficiently good performance, an LTFC-powered car would need to have a radiator with three times the cooling surface area of a comparable diesel-powered vehicle. The second disadvantage is the natural consequence of the first: Operation under heavy load, such as climbing slopes or towing, would not be possible. This would imply the use of oversized cooling systems, with inherent conceptual and functional problems. The operation of cars equipped with conventional internal combustion engines involves higher thermal losses than those using electric motors and fuel cells.

These problems are no longer found in the high-temperature fuel cells made by Volkswagen. The high-temperature membranes ensure that the protons pass through a different kind of liquid electrolyte, phosphoric acid. This substance has good electrolytic properties, similar to water, but its boiling point is at a significantly higher temperature.

The most important benefit of this system is the elimination of the need for a humidification system. The temperature of the current operating regime can be raised to approximately 130ºC without any functional impediment. The high temperature fuel cell developed by Volkswagen is an important contribution towards the production of more compact, lighter and cheaper fuel cell systems.

In short, making a high temperature resistant membrane involves immersing a film in a bath of phosphoric acid. The phosphoric acid soaks into the film in just a few minutes. The membrane is then mounted in the fuel cell element. A sheet of pressed carbon fiber is also placed in the preconfigured fuel cell elements. Air will then be able to circulate through its texture. Then comes the packing and sealing of the element assembly. They are wrapped with carbon fiber sheets that are lined inside with a catalytically active platinum paste, also providing the function of diffusing the feed gases. The coating therefore simultaneously acts as a feed gas distributor and cathode. The membrane impregnated with phosphoric acid is placed in contact with the cathode. Beyond this are layers similar to the cathode, which form the other electrode, the anode. The hydrogen flux is introduced through the texture of the last carbon fiber layer. A space is provided around the elements to provide liquid cooling. All elements are assembled as a battery. An implicit and improtant detail: Conventional electrodes cannot be used in such a fuel cell. However, there is still a problem typical of all fuel cells: Residual water forming in the cathode area. In the case of the HTFC (Figure 19), this would end up damaging the membrane, washing out the phosphoric acid, which acts as the electrolyte. The unintended consequence of this is that the electric current is interrupted. For this reason, all attempts to make an HTFC battery from conventional materials have failed. Intensive research by Volkswagen has revealed the need to configure the electrodes so that residual water cannot get into the membrane area.

Fig 19: HTFC fuel cell

The new type of electrodes have completed the concept. Using a machine that processes materials in layers, similar to those used in semiconductor industry technology, researchers at Volkswagen's Isenbuttel center impregnated several layers of carbon fiber sheets with a material having the consistency of paste and new type properties. The resulting electrodes underwent extensive testing in fuel cells. The desired effect was achieved. Waste water cannot escape from the electrode area. So HTFC technology is now ready for use. It has been demonstrated in practice that high-temperature fuel cells (HTFCs) can operate over a much wider temperature range than previously known cells. In addition, the membrane is less sensitive to impurities in the air due to the higher operating temperature. The use of the high-temperature fuel cells made by Volkswagen makes it possible to dispense with about one third of the components of an LTFC fuel cell system. Thus, HTFC battery systems are lighter, smaller in size and cost less, making them easier to integrate on board a vehicle. That's why this technology offers a real prospect for the future. Peugeot presented the world premiere of the new "207 Epure" (Figure 20) at the 2007 Paris Motor Show. Although it's a single car powered by hydrogen fuel cells, the concept actually features two important elements. The first would be a hint at the design of the 207 CC (Coupe-Cabriolet) series model, while the second is the development of an atypical propulsion system. The car was propelled by an electric motor combined with the new "GENEPAC 20" hydrogen fuel cell, developed by the PSA Peugeot Citroen Group in collaboration with the Atomic Energy Commission. The electricity produced by the fuel cell is intended to support the electric motor or lithium-ion battery when needed. With all elements fully functional, the entire propulsion system provides a range of 350 km at a top speed of 130 km/h.

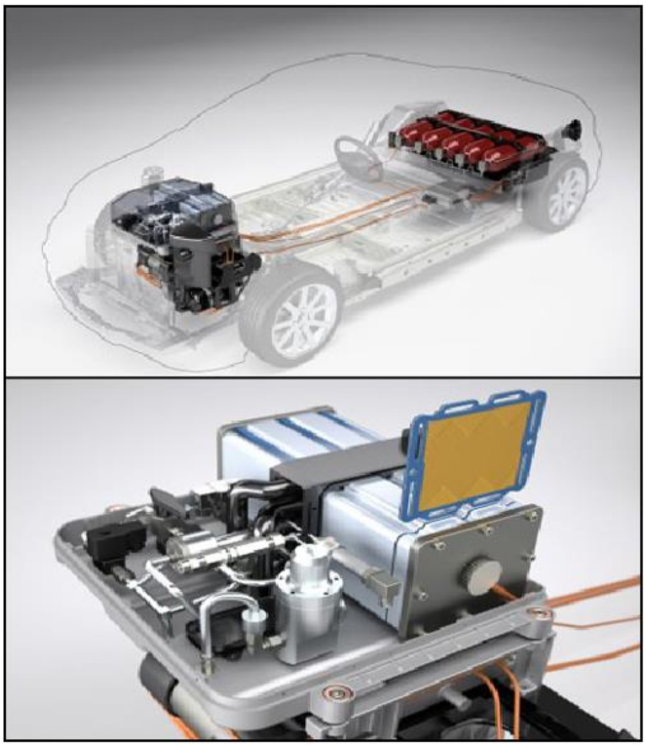

Fig 20: Concept Peugeot 207/2007

Going back to the current period of 2024, while every car manufacturer in the world has at least one electric model for battery-electric propulsion, this is not the case for the hydrogen fuel cell electric car, and the use of this type of propulsion is slowing down, although it is much more efficient and the hydrogen fuel cell electric car has a longer range. Hydrogen cars charge (refuel) in 5 minutes and can travel up to 650 kilometers on a full tank. However, the expensive or polluting production of hydrogen and energy losses up to the fuel pump prevent mass adoption [6].

In recent times, the list of carmakers that have invested tens and hundreds of millions of dollars or euros in developing such vehicles is long. Ford, Nissan, Mercedes-Benz, Fiat, Mazda, Mazda, Kia and Renault are just a few of the manufacturers who have been in the field. But none of them has launched a production model. The Asians are more likely to have done so.

Currently, there are only two hydrogen-powered electric models in production. The one you've probably heard of in one context or another is the Toyota Mirai. Initially launched in 2015, the Toyota Mirai has since reached its second generation and offers 174 horsepower and a range of 650 kilometers, calculated based on the new European WLTP standard. Official fuel consumption is 0.79 kilograms of hydrogen per 100 kilometers, and the three hydrogen tanks have a total capacity of 5.6 kilograms. The other hydrogen powered model currently available on the market is the Hyunday Nexo, which offers 163 horsepower and a range of 666 kilometers (WLTP) via a 6.33 kilogram tank [6].

As can be seen, both hydrogen-powered electric models offer official ranges of around 650 kilometers, slightly higher than the usual 400 to 600 kilometers offered by most battery-electric models. This is because Fuel Cell Electric Vehicles (FCEVs) do not face the disadvantage of cold temperatures in winter (especially in the Nordic countries and elsewhere) which further limit the performance of the

Li-ion battery. The main advantage of FCEVs remains the simple procedure of refueling with hydrogen, similar to refueling cars with gasoline or diesel thermal engines, so you only need about 5 minutes for a full tank.

So there are electric cars with ranges of 650 kilometers that charge in 5 minutes. Okay, so why don't we see them on the streets? Why don't we see any Mirai on Magheru Boulevard in Bucharest, Romania, and no Nexo in the parking lot of the shopping mall we go to so often? Because despite these advantages, there are some major obstacles to mass adoption of this technology [6].

2.8 Disadvantages of using fuel cells

The main disadvantages of using hydrogen fuel cells are:

- the installation is sensitive in case of contact of the two combustible gases;
- the electricmotor voltage of the fuel cell does not remain constant but decreases during operation;
- the cost price of hydrogen on the market is relatively high.

In reality, at the current level of technological development, it seems that those who express reservations are more accurately assessing the possibilities. Analysts who try to remain objective are reserved about the chances of success of the hydrogen economy. Their skepticism is based both on the production, distribution and safety issues involved in using hydrogen and on the rapid progress made, for example, by competing car manufacturers with their 'bienergie' rechargeable battery-electric hybrids with limited range. It should be recalled that there is a hydrogen industry whose pressure group is by no means negligible. The considerations are made taking into account the whole economy based on hydrogen generated by solar or nuclear energy. Public acceptance of change, huge capital investment and the very high cost of hydrogen compared to the current fuel are just some of the issues that have been raised about the new hydrogen economy.

Today the major problems remain:

- Reducing the cost price of hydrogen;
- Creating an efficient hydrogen storage system;
- The constitution of a fuel cell acceptable by performance/price ratio;
- Infrastructure implementation and environmental impact.

Currently the price of filling up a car with hydrogen varies widely and is quite high, reaching 10-15 euros per kilogram. That works out at €50-75 for a full tank of hydrogen. A full tank of hydrogen will not cover more than 650 kilometers. It is expected that if the technology becomes more popular, prices will fall to around €5 per kilogram [6].

According to data aggregated by the H2Stations portal [7], by the end of 2021 there were 685 hydrogen refueling stations globally. Of these, more than 350 stations are in Asia (mainly in Japan and South Korea), while in Europe there are less than 250 stations, the vast majority in Germany, France, the Netherlands and Belgium. The situation of hydrogen refueling station infrastructure by region by 2023 is shown in Figure 21.

In Romania there are currently no hydrogen refueling stations. The nearest one is in Budapest (829 km from Bucharest, the Romanian capital). This filling station was inaugurated in 2021. Another hydrogen refueling station, closer, is about 639 km away in Turkey, in Istanbul, on the Bucharest-Istanbul route.

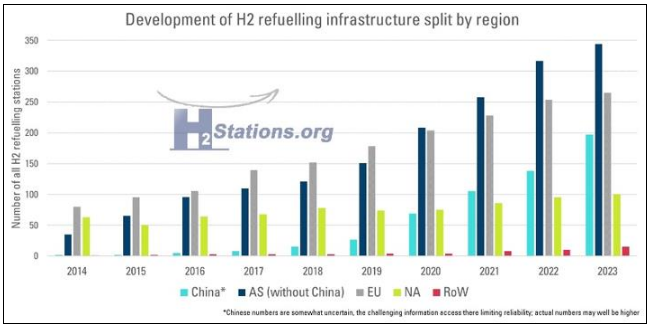

Fig 21: Development of H_2 refuelling infrastructure split by region in the period 2014 - 2023 [7]

One of the explanations for the modest global network of stations is cost. In Europe, opening a hydrogen refueling station requires an investment of about 1 million euro, while in the United States you could easily break the 2 million USD threshold, according to data from the Asia Pacific Energy Research Center (APERC) [6]. In addition, it's not possible to install a hydrogen filling station at home, both for safety and logistical reasons, as you would need a supplier who would only deliver a few kilograms of hydrogen per month.

3. Authors conclusions and personal opinions

An important alternative has been to power cars with electric motors by storing electrical energy in batteries. However, they are inefficient for transporting people or goods within cities, i.e. over limited distances.

One solution is to use fuel cells that use hydrocarbons that carry hydrogen. With minor modifications, this can use the existing distribution network and produce high-performance vehicles whose energy source is no longer limited by the efficiencies imposed by the Carnot cycle. Unfortunately, the main drawback of this propulsion system is the non-renewability of fossil fuels.

Hydrogen and fuel cells have the potential to change the world's energy technology, solving the problems facing the world: Dependence on extracting or importing oil and its derivatives, air pollution, the greenhouse effect, etc. But today, hydrogen and fuel cell technology is more hype than revolution, with advances in (spectacular) fuel consumption and pollution performance that still do not fully justify the full deployment of hydrogen technology.

The realization of the potential of hydrogen and fuel cells depends on the development of specific science and technologies in the field. At national and international level there is a need for a prospective study of the hydrogen economy that will change the way energy is produced and used.

Using hydrogen as an energy source will change many aspects of our lives in the future. Together with the fuel cell, hydrogen has the potential to revolutionize the entire global energy system.

Major breakthroughs in hydrogen production, storage, delivery and utilization technologies are needed if these technologies are to truly become the energy source of the future.

In the early nineties of the last century scientists and engineers developed new concepts and technologies that led to increased efficiency and reduced the cost price per unit of energy produced continuously. Although there is a vision for the hydrogen economy, developing a way to produce, store and use hydrogen is not a simple task that can be solved at the moment. It will still be a long time to establish a pathway at the end of which the full benefits of the hydrogen fuel cell will be found. The first steps towards the future hydrogen economy have been taken, but research and development work is just at the starting point. In the area of hydrogen production and delivery technologies, R&D is mainly addressing the following issues: Biomass and hydrogen production, photolytic processes, distributed production technologies, separation and purification technologies, advanced electrolysis systems, hydrogen production using high temperature thermochemical cycles for water decomposition, hydrogen production infrastructure analysis, etc. In the field of hydrogen storage, R&D projects and experiments with storage materials and technologies have been launched, including basic research aimed at improving the understanding of the fundamental mechanisms of hydrogen storage in hydrides. Numerous researchers are trying to optimize metal hydrides by modifying metal alloys or finely splitting hydrides to increase the reaction surface area.A few years ago it was discovered that a large amount of hydrogen can be stored in carbon nanotubes. These nanometer-long tubes, made only of carbon, can capture hydrogen, but their fabrication is not yet perfected and the cost remains excessive. Other researchers are looking at storing hydrogen in glass microballoons which, because of their small size, could withstand high pressures.

As early as May 2003, the US DOE organized a symposium on storage whose main conclusion was that the government should not subsidize research for hydrogen storage by compression or metal hydrides, government funding should pay attention to innovative technologies such as lightweight metal hydrides like sodium aluminum hydrides or sodium boron hydrides. In the literature it is stated that research should also be carried out for the development of complete integrated portable fuel cell based energy systems, culminating in validation through real world testing. Research efforts have also been directed towards increasing the efficiency of internal combustion engine running on hydrogen as fuel, studying the detonation problem, new injection techniques, and solving the difficult problem of on-board hydrogen storage.

In addition to the electric car, the hydrogen fuel cell powered car is another efficient and clean source of transportation for mankind. By using hydrogen as a fuel source in fuel cells, the oxidation-reduction process converts its energy into energy that powers the electric motors that propel this type of car. Hydrogen is a cheap, efficient, non-polluting but dangerous fuel. It requires sophisticated and sophisticated, and therefore expensive, technologies to store it. However, hydrogen is considered to be the energy source that will provide mankind's future mobility needs.

Another major issue for hydrogen is its energy efficiency from actual production to the car's tank. Or, to put it more simply, one problem is energy losses along the way. According to the study *"The Future of the EU Automotive Sector"* published by the EU in October 2021, the efficiency of hydrogen is only 25% - 35%. And this is true even when hydrogen is obtained through the green process of electrolysis. Thus, up to 75% of the initial electricity is lost on the road: 55% during the hydrogen production process and another 55% of the remaining electricity is lost during the compression, liquefaction and transportation to the hydrogen filling station. By contrast, battery-electric cars are 70% to 90% efficient in terms of electricity use, while fossil fuels are only 10% to 20% efficient. At first sight it is tempting to say that the safety of a hydrogen fuel system is not as high as that of the fuels used. But statistics show that historically, including rockets fueled with liquid hydrogen and liquid oxygen, there have been no major accidents that would classify hydrogen as a more dangerous fuel than gasoline or diesel. Thus, at the fuel pump, the risks are virtually similar to those when filling the tank with gasoline or diesel. In addition, the hydrogen tanks of FCEV electric cars comply with a certain standard that requires a protective flame retardant coating. Also, if the car catches fire and the temperature around the tank rises above a certain threshold, the detection system forces the hydrogen into the atmosphere to avoid an explosion.

From 2000 to the present day, hydrogen fuel cell vehicle propulsion has stalled. This is due to a lack of hydrogen fueling infrastructure, but also to people's skepticism about hydrogen as a fuel. The skepticism has been amplified over the years by the danger of hydrogen in operation.

In my personal opinion, over and above these considerations, the big challenge for end-user acceptance of this fuel alternative is the instability of hydrogen itself. Hydrogen in liquid form is quite difficult to manage, requires special transportation methods and has to be stored at high pressures. Vehicle hydrogen tanks require special construction and must be shielded with explosion-proof materials (e.g. Kevlar), as hydrogen can explode in the event of a car accident. Pipes and fittings of hydrogen fuel systems must be perfectly watertight and away from any source of heat, because hydrogen ignites when in contact with hot engine parts. These are some of the reasons why people do not want such cars.

Based on these aspects of hydrogen production, transportation and charging infrastructure, it's not hard to guess that sales of hydrogen electric cars have so far been rather modest.

Data collected by research company IDTechEx shows that only 15,538 Mirai and Nexo units have been sold globally through 2021. Yes, up 82% compared to 2020, but there are some less pleasant explanations behind this percentage. For example, 38% of the 5,918 Mirai units were sold in Japan, while in the US state of California the price of a Mirai was only $18,000, as Toyota offered a special $20,000 discount and the subsidies from the US authorities was $12,500. Bonus: Customers get free hydrogen refueling for the first three years of use up to $15,000. Meanwhile, 88% of the 9,620 Hyundai Nexo units were sold in South Korea, where the discount granted by the authorities was the equivalent of about $30,000. That's about 50% of the list price. The discounts offered by manufacturers and national authorities are even higher than those received by buyers of battery-electric cars, even when compared with Romania, which offers the most generous purchase bonus: 45,000 lei, equivalent to more than €9,000.

With all these impediments and disadvantages of using hydrogen to power on-road vehicles, Asian manufacturers such as Toyota and Hyundai continue to invest significant sums in the development of hydrogen electric cars. BMW is currently building a new plant in Decebren (Hungary), to be completed in 2024 and dedicated solely to zero-emission vehicles developed on a new platform, the Neue Klasse. The German carmaker recently confirmed that the platform will also allow the development of hydrogen-powered electric models.

We personal opinions is that hydrogen will still be the energy source that will meet mankind's mobility needs in the future. The hydrogen fuel cell car will gain the lead at the expense of the electric car. We justify this statement by the following: At the moment, the issues related to the autonomy of electric batteries are evolving slowly, and taking into account factors such as low temperatures in winter (significantly decrease the capacity of an electric battery), driving at high speed, sudden acceleration of the car and going up ramps (quickly consumes the energy in the battery), use of air conditioning in winter and air conditioning in summer (substantial energy consumption), and finally the physical wear and tear over time of the electric battery (similar to the electric battery in a cell phone, which, due to wear and tear, decreases in capacity over time), make the electric car unattractive. Add to all this the dependence on electric charging stations (in our country, few in number, located in the parking lots of large stores in urban areas and almost non-existent on highways, expressways or national roads). It is also easier and more comfortable for us, like any other user, to fill up the tank with gasoline or diesel and drive 1,000-1,200 km without stress and without worrying about refueling. At the moment, the hybrid car provides the greatest comfort from this perspective, but it is important to bear in mind that carbon-based fuels will soon run out. Research into the hydrogen fuel cell car will have to be stepped up. The safety of hydrogen involves technology, and this costs more than research into developing the autonomy of electric batteries at this time. A hydrogen fuel cell is more efficient, more reliable and has a longer lifespan, but is more expensive compared to an electric traction battery. The cost prices of raw materials to manufacture electric batteries, such as lithium, cobalt and nickel, as well as the cost price of electric battery components, have pushed up the value of the packs to $151/kWh. This is a 7% increase in 2022 compared to 2021. Their prices are expected to rise in the years to come (152 USD/kWh in 2023 and so on). The electric car industry argues that the price of 100 USD/kWh for an electric traction battery pack is the benchmark at which the electric car becomes competitive with the conventional, heat-engined car. Since the beginning of 2021, the price of the raw materials from which electric batteries are made have risen enormously (lithium has risen about tenfold, nickel has risen by over 74%, and the price of cobalt has doubled since 2020). All these increases become a big problem for the green car market. It is believed that these increases would have been even higher if the Chinese market had not stepped in with cheaper lithium iron phosphate (LFP) battery packs, which have a shorter range. By 2022, energy demand for manufacturing electric cars in the global market has doubled to 603 kWh for Li-ion materials. For this reason, an acute shortage of semiconductors was observed in 2022 and some electric vehicle manufacturers had to reduce their production. The cost price of electric battery packs on the world market varies significantly, so that in China the price is 127 USD/kWh, while in the USA the price has reached 157 USD/kWh, and in Europe the price has reached as high as 169 USD/kWh.

4. References

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