SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2023
ORGANIZATION AND MANAGEMENT SERIES NO. 182

IMPACT OF HYDROGEN CELLS ON ECONOMIC EFFICIENCY AND THE ENVIRONMENT ACCORDING TO RENEWABLE ENERGY STANDARDS

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Purpose: The research goal of the work is to determine the levels of profitability of hydrogen cells and their impact on the environment. The authors of the article answer the question under what boundary conditions there is an economic justification for the use of hydrogen cells in various branches of the economy while respecting environmental regulations and standardizing energy production by the principles of a sustainable economy.

Design/methodology/approach: The research was carried out using economic measurement model methods. These methods allowed the authors to calculate the market value of the investment with the assumed boundary criteria and to determine the economic effectiveness of the analyzed research problem. Additionally, the authors analyzed the problems of the widespread use of hydrogen in terms of its storage in technical, technological and economic terms.

Findings: Research has shown that it is possible to obtain up to 7% by weight. hydrogen relative to the mass of the metal. Carbon nanofibers may become the material of the future for making hydrogen tanks. The use of fuel cells brings many benefits: simple structure and operation, neutral impact on the environment, and low noise level. Moreover, hydrogen fuel cell technology allows for efficient operation for a long time and the possibility of high momentary overloads, which allows for considerable scalability and wide application with economic justification.

Practical implications: The presented models have shown that the project of their implementation is fully economically justified and will allow investors to make a rational investment decision.

Originality/value: The original contribution of this work is the implication of the data on real research models. This data allowed the authors to make calculations and indicate directions of improvement for the construction of innovative hydrogen cell solutions as part of the standardization of regulations on renewable energy sources in various sectors of the economy.

Keywords: Hydrogen, hydrogen storage, fuel cells.

Category of the paper: Research paper.

http://dx.doi.org/10.29119/1641-3466.2023.182.18

1. Introduction

With the development of civilization and its accompanying technologies, the demand for energy increases. For decades, humanity has not thought about the size of deposits of natural raw materials from which energy is mainly obtained. Over the last few years, attention has been drawn to the possible problem of depletion of fossil fuel deposits. Government institutions and companies from the fuel and energy sector have started looking for a new energy source. This is not the only problem that exists. As deposits are depleted, the price of raw materials gradually increases, which translates into an increase in the price of final products. There may be concerns about a situation in which the population will not be able to use energy due to a lack of access to natural resources or for financial reasons. One of the most likely solutions is the introduction of hydrogen cell technology, which would replace current energy sources. This is due to its universality the occurrence of hydrogen in nature, which serves as fuel in hydrogen cells. This technology can be used in all segments that require power. Hydrogen cells are most widely used in the drive system of vehicles. The size of available cell types allows the technology to be tailored to the required application in such a way as to ensure the highest possible system efficiency. The first step to introducing hydrogen cell technology will be to find solutions for many technological and economic reasons.

The work aims to present the power supply possibilities offered by hydrogen cell technology and the ecological and economic feasibility of its implementation and use.

The article presents the reasons for searching for new energy sources and describes in detail the properties of hydrogen, methods of its acquisition and possibilities of its storage and transport. The research part determined the impact of the use of hydrogen in various applications on the environment and the economic benefits resulting from the use of the new power source.

2. Review of the Research Problem

2.1. The essence of the research problem

Hydrogen is already widely called the "fuel of the future" and may be one of the alternatives to replacing fossil fuels. Hydrogen is an important industrial raw material, mainly used in the petrochemical and refining industries, and is also used in the synthesis of many products important for the economy and for the production of methanol, ammonia, urea, hydrochloric acid, ethers, and higher alcohols (Folentarska et al., 2016). Hydrogen is not a primary energy source but can be used, like electricity, as an exchange method to obtain energy where it is required. As a renewable and emission-free energy source, hydrogen can find many portable and stationary applications. As an energy carrier, hydrogen can increase energy diversification and security by reducing our dependence on hydrocarbon-based fuels. Hydrogen is different from other energy sources. Together with electricity, they complement each other and one can be transformed into the other. Together with energy electricity are complementary and one can be transformed into the other (Bioenergy International, 2020). It can be perceived as an energy source whose quality does not depend on the method in which it is produced or the source from which it comes. Hydrogen molecules produced during water electrolysis are identical to those produced from plant biomass, paper, coal gasification or natural gas. It is the basic chemical substrate in the production of gasoline, fuel oil, lubricants, fertilizers, plastics, paints, detergents and pharmaceutical products. Moreover, it is an excellent metal refining agent and an important preservative.

Hydrogen has the best energy-to-mass ratio, which is the justification for using it as a fuel in space vehicles. An important factor for assessing fuel quality is the fuel energy density, which provides information about the packing density of hydrogen atoms in the fuel. As the number of carbon atoms contained in a fuel molecule increases, the energy density decreases and, conversely, as the number of hydrogen atoms increases, the energy density increases. Based on these relationships, the superiority of hydrogen as a fuel over currently used fuels can be demonstrated. For example, a 500 dm^3 tank containing 408 kg of diesel oil will contain the same amount of energy as a tank containing 8000 dm^3 of hydrogen at a pressure of 25 MPa (Collins, 2020). This means 16 times greater tank capacity with a hydrogen content of 150 kg. In the case of liquid hydrogen, the same amount of diesel oil will be equal to a hydrogen tank with a capacity of 2100 dm^3, which in this case gives 4.2 times greater capacity (Ouyang et al., 2018).

Hydrogen can be obtained from many sources because it occurs almost everywhere, from biological tissues and DNA to crude oil, gasoline, paper and water. Moreover, it can be produced in nuclear, solar, wind, hydroelectric power plants, thermal power plants or from plants (Li et al., 2019). What remains is to develop cost-competitive, efficient and fast methods of production, transport and storage. Currently, hydrogen is produced in the world from natural raw materials in the following percentages: natural gas - 48%, crude oil - 30%, coal - 18%, and water electrolysis - 4% (Niekurzak, 2021). Hydrogen is obtained through steam reforming of methane, gudron gasification, coal gasification and water electrolysis. The selected form of hydrogen storage must be appropriately matched to its applications. Table 1 shows an example of storing the amount of hydrogen (depending on its state) and methane, methanol and ethanol.

Table 1.
Energy value and density for various types of hydrogen, methane and biofuel

Form of storage	Energy value		Density
	kJ/kg	MJ/dm^3	kg/dm^3
Hydrogen (gas approx. 0.1 MPa)	120 000	0.001	0.00009
Hydrogen (gas approx. 20 MPa)	120 000	1.9	0.015
Hydrogen (gas approx. 30 MPa)	120 000	2.7	0.022
Hydrogen (liquid)	120 000	8.7	0.072
Methane (gas approx. 0.1 MPa)	56 000	0.0374	0.0007
Methanol	21 000	17	0.0008
Ethanol	28 000	22	0.0008

Source: own based (Sørensen and Spazzafumo, 2018).

Many commercially available technologies are used to store hydrogen. The most popular method is the use of high-pressure tanks available in various sizes and used in various pressure ranges. One such solution is large underground storage facilities, where hydrogen can be stored underground in caves, aquifers and spaces left after oil and gas extraction. In most cases, hydrogen is stored in pressure vessels. Currently, the best solution is ultra-light composite materials that can withstand pressures above 20 bar (Rogala, 2022). Additionally, hydrogen can be stored in liquid form in tanks. The technology of producing hydrogen in liquid form requires large energy inputs. The compressed hydrogen must be cooled to a very low temperature (20.28 K, -423.17 °F/−252.87 °C) (Sánchez, 2021). The main advantage of storing hydrogen in liquid form instead of gas is that it takes up much less space. When hydrogen is converted into a liquid state, it can be stored in special thermal high-pressure tanks. Hydrogen can also be stored as metal hydrides at moderate temperatures and pressures, which favours this technology over storing hydrogen as compressed or liquid gas. Therefore, storage in the form of metal hydrides is a good solution in vehicle construction. Research is still ongoing to find more efficient methods of storing hydrogen. One of the modern methods is to store hydrogen in carbon nanotubes (Sørensen, Spazzafumo, 2018). Carbon nanotubes are unique structures with amazing electrical and mechanical properties. One possibility is to create a super-strong composite material made from carbon nanotubes and polymers, which could be used in all kinds of new engineering structures (He et al., 2015). This would enable the construction of a tank that would withstand very high temperatures the pressure of stored hydrogen, used as fuel in fuel cells, the creation of super-bulletproof vests and indestructible clothing, and the construction of much more durable spacecraft.

2.2. Energy and climate strategies and hydrogen energy

Hydrogen is one of the pillars of the EU Green Deal, paving the way to a climate-neutral economy by 2050 by eliminating fossil fuels from transport, but also from industries that are difficult to decarbonize, such as the steel and chemical industries (Hauenstein et al., 2020). In July 2020, a document titled "Building a hydrogen economy for a climate-neutral Europe", is a working version of the EU strategy. The European Commission announced that it will take action to ensure that hydrogen constitutes 12-14% of the Community's energy mix by 2050.

Currently, the main source of hydrogen in the world is a process called "natural gas steam reforming" (Graetz et al., 2017). However, the accompanying carbon dioxide emissions are slightly lower than in the case of an internal combustion engine. Therefore, hydrogen obtained this way is commonly called "grey". A slightly less environmentally harmful method, because it uses CO_2 sequestration technology (capture and storage), is methane pyrolysis. Natural gas (hence the name: ("blue" hydrogen) is heated to high temperatures to separate hydrogen from carbon, which becomes solid and can be further used as a raw material. However, the real alternative to "grey" hydrogen is "green" hydrogen, obtained from surplus electricity from renewable sources and subjected to the electrolysis of water, i.e. decomposition into hydrogen and oxygen (Wang et al., 2019). Connecting wind turbines/solar panels to electrolyzers that split water into primary components would allow energy to be stored when there is excess production from renewable energy sources.

The European Commission is focusing on the development of "green" hydrogen, which is still rare while allowing low-emission "blue" hydrogen (the emissions associated with it are eliminated using carbon capture and storage technology) and completely rejecting "grey" hydrogen. The authors of the EU hydrogen strategy made an optimistic assumption that approximately half of the current hydrogen production from fossil fuels can be converted into low-emission ("blue" hydrogen) (Meyer, 2021). The European Greens claim that these estimates are inflated due to the dictates of the gas lobby. In their opinion, this lobby influences the climate commissioner and vice-president of the European Commission, Franz Timmermans. The International Association of Oil and Gas Producers (IOGP) warns that the EU hydrogen strategy will be doomed to failure if it focuses solely on the production of hydrogen from renewable energy sources, ignoring other low-emission sources, such as nuclear and methane pyrolysis.

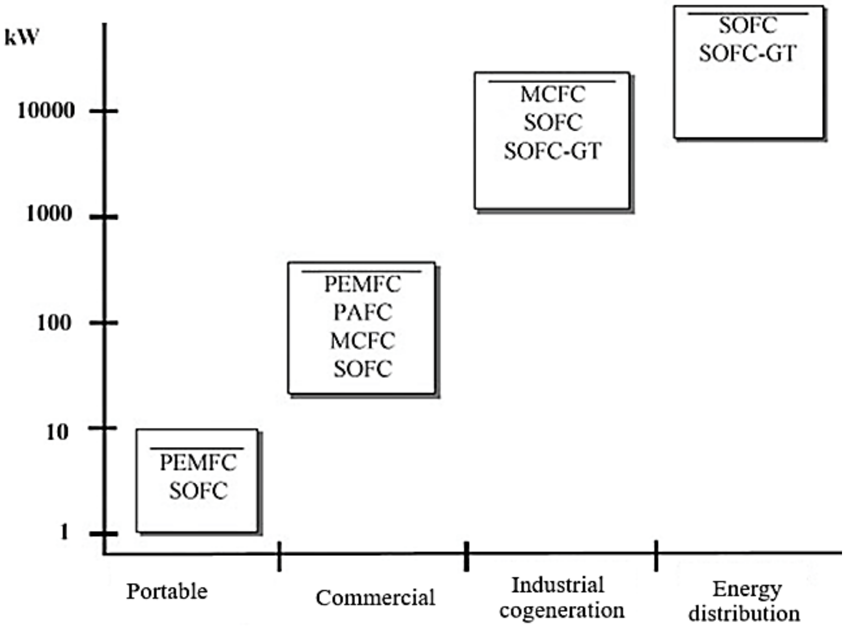
One of the conditions for the success of the hydrogen revolution is to reduce the price of gas to 1-2 euros per kilogram (1 kg of hydrogen allows you to travel approximately 100 km) (Niekurzak et al., 2022). Brussels wants to achieve this goal by increasing the density of the electrolyzer network throughout the Community and increasing the installed capacity to at least 40 GW over the next decade. The amount of investment in electrolysers is expected to amount to EUR 13-15 billion over the next 10 years (Jaworski et al., 2019). Additionally, EUR 50-150 billion is needed to invest in wind and solar energy for hydrogen production. In turn, the EU will spend EUR 120-130 billion on hydrogen transport, storage and refuelling stations (Mikulik, Niekurzak, 2023). The existing natural gas and LNG infrastructure will be reviewed to expand its application spectrum to include hydrogen to optimize costs. The total volume of investments in building adequate hydrogen production capacity by 2050 may amount to nearly EUR 0.5 trillion (Takach et al., 2022).

It is estimated that by 2050, renewable energy sources could constitute a significant part of the European energy mix, in which the share of hydrogen could increase to 20%, in particular in terms of its use in transport and industry (Hydrogen Strategy…). According to sources from the bodies of the European Parliament (Directorate-General for Communication) (Hydrogen Strategy...), the European Parliament currently expects, in addition to "encouragement to stimulate demand and the creation of a European hydrogen market and the rapid implementation of hydrogen infrastructure", also a certification system for all imports hydrogen, as well as "assessing the possibility of changing the purpose of existing gas pipelines for the transport and underground storage of hydrogen". In recent years, the role of hydrogen in energy policy has been increasing (Nguyen et al., 2020) and (Starobrat, 2020) and (Ministerstwo Klimatu i Środowiska, 2019). As in Poland, we are responsible for the production of approximately one megaton of hydrogen per year, which constitutes 14% of hydrogen demand in Europe.

2.3. General characteristics of fuel cells

A fuel cell uses the chemical energy of hydrogen or other fuels to produce electricity cleanly and efficiently. If the fuel is hydrogen, the only reaction products are electricity, water and heat (Romański, 2007). Fuel cells are unique in the variety of their potential applications, they can use a wide range of fuels and raw materials, and supply energy to systems as large as a municipal power plant and as small as a laptop. Hydrogen fuel cells can be used in a wide range of applications, providing power for applications in many sectors, including transport, industrial buildings, commercial buildings, residential buildings and long-term grid energy storage in reversible systems (Hemme, Van Berk, 2018). Hydrogen cells have several advantages over conventional fossil fuel technologies currently used in many power plants and vehicles. Fuel cells can operate at higher efficiency than internal combustion engines and convert energy chemicals in the fuel directly into electricity with an efficiency exceeding 60% (Castilla-Martinez et al., 2020). Fuel cells have lower or zero emissions compared to internal combustion engines. Hydrogen fuel cells only emit water, which addresses critical climate challenges because there are no carbon dioxide emissions. No air pollution causes smog and health problems at the place of operation. Cells are used to build batteries for portable devices, low- and medium-power generators, and stationary power plants. They are also widely used in transport, both in passenger cars and in public transport (Boateng, Chen, 2020). They are also expected to be used in heavy, air and sea transport. Which car drive will be the most effective and at the same time the cheapest? Battery or fuel cell using hydrogen? We can be sure of one thing - the drive of the future will be a vehicle with the most... lower emissions. The need to reduce dependence on fossil fuels and reduce CO_2 emissions has become an impulse to search for new energy sources and develop electromobility (use of electric vehicles, i.e. EV) (Wijayanta et al., 2019).

In fuel cells, the chemical energy of the fuel is directly converted into electrical energy. This type of conversion is an important advantage of cells because the efficiency of converting one form of energy into another is not subject to the limitations resulting from the theory of heat engines. Therefore, it is possible to achieve efficiency exceeding the efficiency of heat conversion into mechanical energy at the currently controlled temperatures of heat supply to the circuit in which the heat engine (steam or gas turbine) operates. In the energy industry, fuel cells are considered to be used in small and medium-power units, including as distributed sources of heat and electricity (Wan et al., 2019). There are many criteria for classifying fuel cells. The basic division includes links for the direct use of a given fuel and the indirect use of its conversion (reforming) (Surygała, 2008). A typical representative of the first group is a cell powered by hydrogen and oxygen. The cell to which methane or biogas is supplied and oxidizer belongs to the second type of cell. An important division criterion here is the cell operating temperaturę (Niekurzak, Kubińska-Jabcoń, 2021). The application possibilities of hydrogen cells are very wide and promising. Depending on the type of application, the type of cell that will be best suited to perform the desired function changes (Han et al., 2008). The powers required by the market in which the cell will be used affect both its type and the costs of the entire installation. Therefore, this determines the purpose of different types of cells for different sectors. This division is presented in (Figure 1).



PEMFC – proton cell with replaceable polymer membrane.
SOFC – solid oxide cel.
MCFC – ogniwo ze stopionymi węglanami.
PAFC – ogniwo z kwasem fosforowym jako elektrolit.
SOFC-GT – solid oxide cell with gas turbine.

Figure 1. Market sectors for fuel cells.

Source: own.

The basic idea of using hydrogen cells is to use them to power passenger cars, buses and trucks, ships, trains and planes. In addition, they are used as stationary energy generators, integrated home systems to power portable devices or hydrogen highways.

3. Materials and Methods

3.1. Efficiency of hydrogen cells

The thermal efficiency of an energy conversion device is defined as the ratio of the amount of useful energy produced to the change in chemical energy contained in the fuel, called thermal energy. Useful energy is obtained during the reaction of fuel and oxygen, it is also called non-volume work. This relationship is given by the formula:

$$\eta = \frac{\text{useful work}}{\Delta H} \tag{1}$$

where:

ΔH - the total caloric value of the reaction (including combustion reaction),

η - thermal efficiency of the device.

Typically, chemical energy from fuel is first converted into heat, which is then converted into mechanical energy, which in turn can be converted into electrical energy. A heat engine is used to convert thermal energy into mechanical energy (Brückner, et al., 2014). In a fuel cell, chemical energy is directly converted into electrical energy.

$$\Delta G = \Delta H - T\Delta S \tag{2}$$

where:

ΔG – the maximum amount of work that can be obtained during a chemical change,

ΔH - the total caloric value of the reaction (including combustion reaction).

It follows that the theoretical efficiency of the reaction (assuming its ideal conditions) is determined by the relationship:

$$\eta = \frac{\Delta G}{\Delta H} = \frac{\Delta H - T\Delta S}{\Delta H} \tag{3}$$

In the case of chemical reactions, as in thermodynamic processes, the maximum work of an isothermal-isobaric reaction can be considered, which is determined by the relationship:

$$L'_{max} = G_1 - G_2 = nFE \tag{4}$$

where:

L'_{max} – maximum work of the isothermal-isobaric reaction,

$G_1 - G_2$ – free enthalpy change,

n – number of electrons transferred during the reaction,

F – Faraday's constant (determines the number of units of electric charge - coulombs - per 1 mol of reaction),

E – is the electromotive force of the cell.

The most commonly used fuel cell efficiency is based on the change in the free enthalpy of the reaction that occurs in the cell:

$$\mathrm{H_2} + \frac{1}{2}\mathrm{O_2} = \mathrm{H_2O} \tag{5}$$

resulting from:

$$\Delta \mathrm{G}_\mathrm{r}^{\circ} = \underline{\mathrm{G}}^{\circ}_{\mathrm{H_2O}(\ell)} - \underline{\mathrm{G}}^{\circ}_{\mathrm{H_2}} - \frac{1}{2}\underline{\mathrm{G}}^{\circ}_{\mathrm{O_2}} \tag{6}$$

in which water is created in the form of liquid. Under standard conditions of 298 K and a pressure of 0.1 MPa, the chemical energy for the hydrogen/oxygen reaction is 285.8 kJ/mol, while the achieved free work energy for useful energy is 237.1 kJ/mol (Fellay et al., 2008). Based on this, it follows that the thermal efficiency for an ideal cell operating in a reversible process on pure hydrogen and smouldering under normal conditions would be:

$$\eta_{\mathrm{ideal}} = \frac{237{,}1}{285{,}8} = 0{,}83 \tag{7}$$

The efficiency of currently existing fuel cells is defined as the ratio of voltages in real and ideal states. For a fuel cell using the reversible conversion of hydrogen and oxygen at a pressure of 0.1 MPa, the ideal voltage at a temperature of 298 K is 1.229 V. The thermodynamic efficiency of a fuel cell operating at voltage V_{real}, based on the higher calorific value of hydrogen, is described by the relationship:

$$\eta = 0{,}83 \times \frac{V_{real}}{V_{ideal}} = 0{,}83 \times \frac{V_{real}}{1{,}229} = 0{,}675 \times V_{real} \tag{8}$$

The efficiency of a fuel cell is determined by the voltage, which in turn corresponds to the current density. The cell can operate at different current density values, which are expressed as $\frac{mA}{cm^2}$. As the current density decreases, the cell voltage and its efficiency increase. However, to maintain the same power of the cell while reducing the density, its active surface must be increased (Wang et al., 2020) and (Yildirim, Farha, 2018). This means an increase in investment capital along with an increase in efficiency and a decrease in operating costs.

3.2. Losses occurring in the fuel cell

Fuel cell performance is lower than its ideal potential. This is caused by irreversible losses, which are presented in (Figure 2). These losses are often referred to as polarization, overpotential and overvoltage.

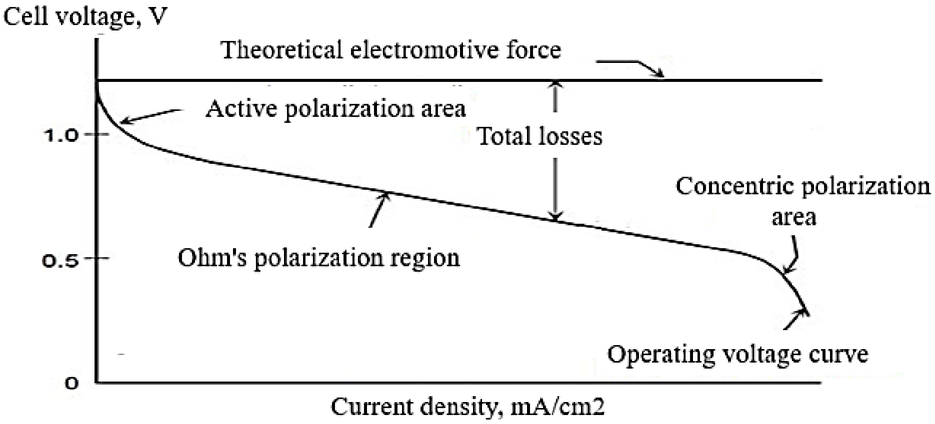


Figure 2. Ideal and actual fuel cell voltage.

Source: own.

The sources of losses are:

- activation polarity,
- ohm polarization,
- concentration polarization.

Activation losses result from the activation energy of electrochemical reactions at the electrodes. It depends on the speed at which these reactions occur. The following factors contribute to the activation polarization: the process of reactant absorption, electron transfer and the type of electrode Surface (Xiao et al., 2020). Ohmic losses are caused by the resistance to the flow of ions in the electrolyte and electrodes. They are proportional to the current density and depend on the selected material, slope geometry and temperature. Concentration polarization is caused by the slow occurrence of electrochemical reactions resulting from the conditions of diffusion of reactants through the electrolyte. It is strongly influenced by current density, reactant activity and electrode structure.

3.3. Properties of fuel cells

Table 2 presents the reactions occurring in fuel cells depending on their type.

Table 2.
Electrochemical reactions in fuel cells

Cell type	Anodic reactions	Cathodic reactions
PEMFC	$H_2 \rightarrow 2H^+ + 2e^-$	$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$
AFC	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$	$\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2OH^-$
PAFC	$H_2 \rightarrow 2H^+ + 2e^-$	$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$
MCFC	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$	$\frac{1}{2} O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$
SOFC	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	$\frac{1}{2} O_2 + 2e^- \rightarrow O^{2-}$
	$CO + O^{2-} \rightarrow CO_2 + 2e^-$	
	$CH_4 + 4O^{2-} \rightarrow 2H_2O + CO_2 + 8e^-$	

Source: own based (Sørensen, Spazzafumo, 2018).

A summary of the operating conditions of individual fuel cells is presented in Table 3.

Table 3.

Basic operating conditions of fuel cells

Conditions work	Cell type				
	PEMFC	**AFC**	**PAFC**	**MCFC**	**SOFC**
Electrolyte	perfluoro sulfonic acid (ion exchange membrane)	KOH solution in the matrix	concentrated H_3PO_4 in the matrix	molten Li and K carbonates	ceramic ZrO_2 yttrium stabilized
Working temperature	353 K	338-493 K	478 K	923 K	873-1273 K
Load carrier	H^+	OH^-	H^+	CO_3^{2-}	O^{2-}
Catalyst	Pt	Pt	Pt	Ni	perovskite
Possible fuels	H_2, CH_3OH	H_2	H_2	H_2, CO, hydrocarbons	H_2, CO, hydrocarbons
Reformer	external	external	external	internal	internal
The role of gases:					
CO	poison > 50 ppm	poison	poison > 0,5%	fuel	fuel
CH_4	thinner	poison	thinner	fuel	fuel
CO_2 i H_2O	thinner	poison	thinner	thinner	thinner
H_2S i COS	poison	poison	poison > 50 ppm	poison > 0,5 ppm	poison > 1,0 ppm

Source: own based (Sørensen, Spazzafumo, 2018).

Due to the low-temperature operation of PEMFC, AFC, and PAFC cells and the use of highly active platinum catalysts, the use of pure hydrogen and oxygen raw materials is required to obtain satisfactory efficiency. In the case of high-temperature MCFC and SOFC cells, due to the high operating temperature, platinum catalysts are not required, which allows the use of H2, CH4 (methane), CO and heavier hydrocarbons as fuel. However, they are sensitive to the presence of sulfur compounds H2S and COS in the fuel. Table 4 shows the operational advantages of fuel cells (Lhuillier et al., 2020).

Tabela 4.

Usable advantages of fuel cells

Fuel Type	**Electrical efficiency, %**	**Power density, MW/cm^2**	**Power range, kW**	**Application**	**Advantageous features**	**Unfavorable features**
PEMFC	40-50	300-1000	0.001-1000	- transport, - electricity generation, - power supplies	- low operating temperature, - fast start, - no corrosion	- expensive catalytic converter, - high sensitivity to poisons
AFC	50	150-400	1-100	- space research, - army	- fast start, - high efficiency	- expensive catalytic converter, - sensitivity to poisons
PAFC	40	150-300	50-1000	- transport, - electricity production	- cogeneration efficiency up to 85%, - resistance to poisons present in H_2	- necessary catalyst Pt, - low-efficiency electric, - large mass and volume
MCFC	45-55	100-300	100-100000	- electricity production, - heat production	- high efficiency, - fuel flexibility, - catalyst flexibility	- high corrosiveness, - high failure rate, - expensive materials
SOFC	50-60	250-350	100-100000	- electricity production, - heat production	- high efficiency, - fuel flexibility, - catalyst flexibility	- expensive high-temperature materials, - difficulties with seals

Source: own based (Sørensen, Spazzafumo, 2018).

Despite great efforts put into the development of fuel cell technology, as a source of clean energy production, this technology is only in the initial stage of development. For this technology to enter everyday life, there must be an improvement in the strength and reliability of materials, a reduction in the size and weight of devices, an improvement in water and heat management and a reduction in the costs of energy obtained (Assfour et al., 2010). Engines using fuel cells should demonstrate reliability and durability at the level of currently produced internal combustion engines, i.e. approximately 5000 hours (300,000 km) of operation, and the operating temperature should be 313-353 K (Dorociak, Tomecki, 2019). As for stationary systems, their reliability should exceed 40,000 hours, and the operating temperature is in the range of 238-313 K.

4. Results and discussion

4.1. The impact of hydrogen cell technology on the environment

A very big challenge for any new technology that is to be widely commercially used is to demonstrate its benefits. They must be significant enough to outweigh the disadvantages associated with newer technology, e.g. higher costs than currently used technologies. In the case of hydrogen cells, the arguments in favour of them are the benefits of a direct, positive impact on the environment and the quality of people's lives. "Environmental" factors include such aspects as air, water, soil and fauna and flora pollution, noise level, and impact on the landscape. All these factors must be considered on both a global and local scale, including the impact on the climate through greenhouse gas emissions or substances that deplete the ozone layer. Additionally, there are factors determining the impact of technology on human life, its safety and the level of satisfaction needs. As part of the research, three vehicles were compared and their utility values were compared depending on the drive used. The comparison participants included a Toyota Camry powered by a gasoline engine, a VW Lupo 3L equipped with a diesel engine and a Daimler Chrysler "f-cell" powered by hydrogen cells. These vehicles differed significantly in their construction, as shown in (Figure 3), which shows the masses of individual vehicle elements. It is worth noting that Daimler Chrysler and VW Lupo were vehicles of similar size, while Toyota is the largest of them. It can be observed that the cell vehicle, despite its much smaller size, was larger than the Toyota. The biggest impact on weight was the body, chassis and the entire drive system, which is almost twice the weight. The weight of the vehicle adversely affects both its performance, which is weaker than that of traditional vehicles and its range, which is extremely important for the vehicle's usability. The latest designs provide a range allowing normal use of the vehicle.

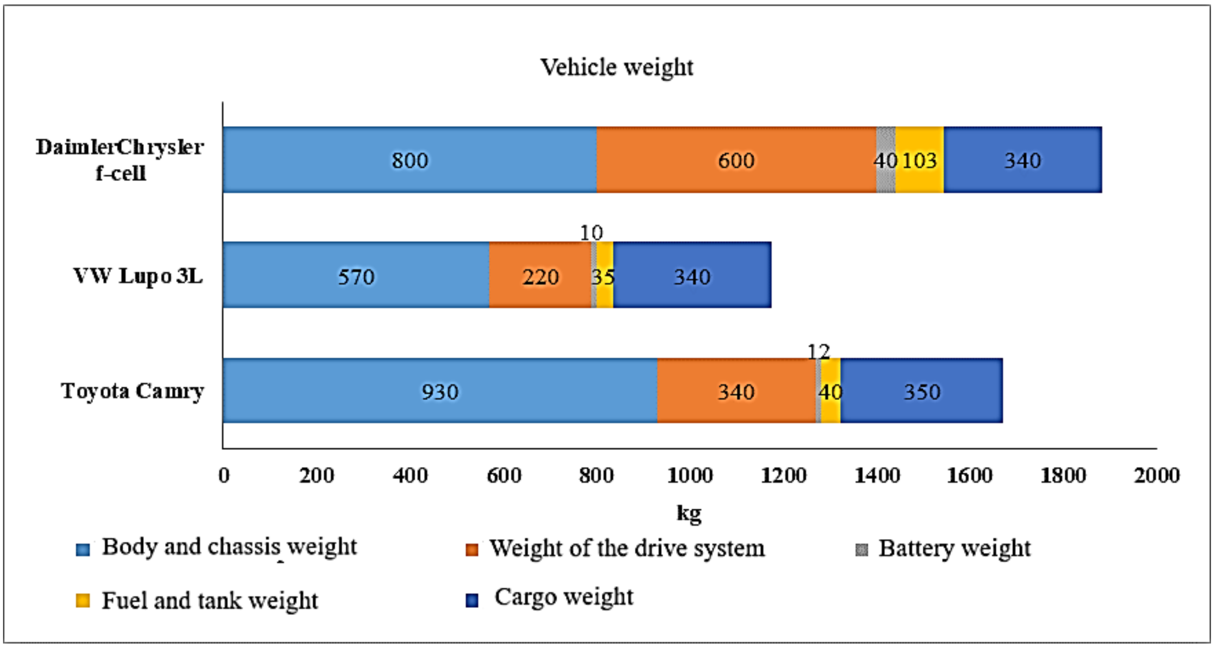


Figure 3. List of vehicle masses with various types of drive.

Source: own-based (Surygała, 2008).

The main aspect in favour of hydrogen cells is their beneficial impact on the environment. Combustion vehicles emit greenhouse gases during operation, while the cells produce heat and water. It can therefore be concluded that hydrogen cells are a "clean" technology, however, assuming that only the operation of the cell itself is taken into account. Greenhouse gas emissions may occur at the hydrogen production stage, which depends on the production method used. Figure 4 shows the emissions of individual compounds.

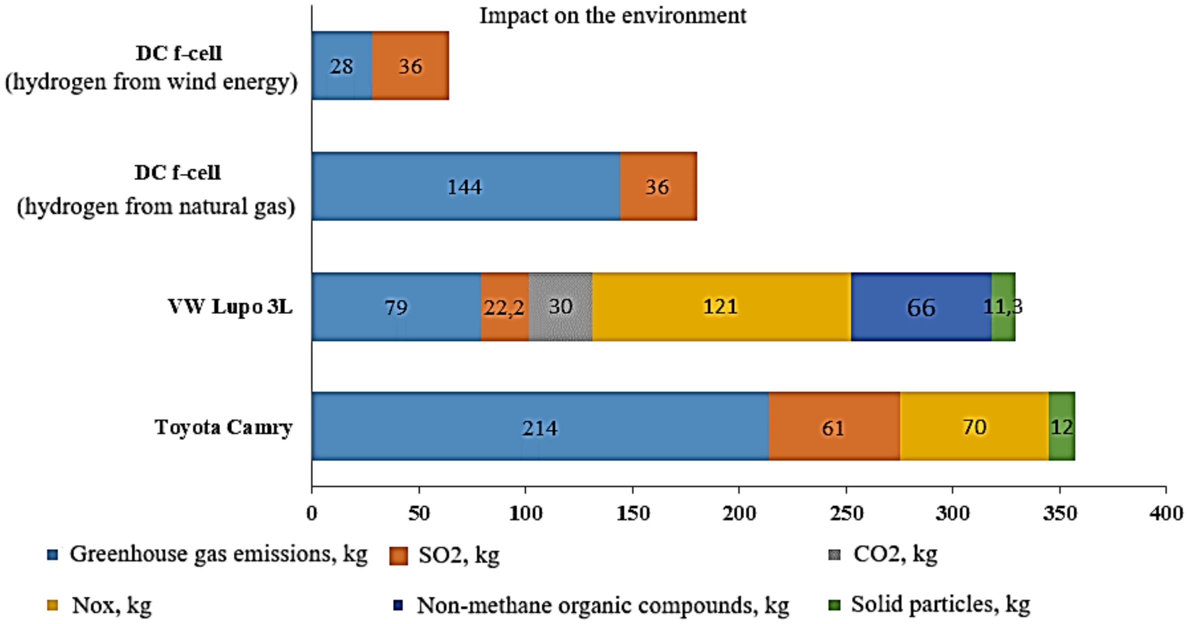


Figure 4. Summary of the environmental impact of vehicles with different types of drive.

Source: own-based (Surygała, 2008).

The emissions level of Chrysler's Daimler vehicle was divided according to the hydrogen production process. You can see that there is a huge difference between obtaining hydrogen from electrolysis using wind energy and the process based on natural gas. However, despite the production of greenhouse gases during the production process, their level is much lower than in a combustion vehicle. In the case of a diesel engine, fewer greenhouse gases are produced than in the case of a Daimler Chrysler vehicle, but in addition to them, several other harmful compounds are also produced. As a result, the ecological advantage of cells over combustion engines is huge.

Another summary of the level of carbon dioxide emissions is presented in (Figure 5) taking into account the latest production technology and EU standards. The data was divided according to the type of vehicle and the fuel used. Pollutants generated during hydrogen production were also taken into account. Analyzing the data of combustion vehicles, it can be seen that over the next ten years, there will be a significant improvement in the environmental friendliness of gasoline-powered vehicles, but their emission level is still much higher (more than twice as compared to vehicles with hydrogen cells, for which hydrogen is obtained from natural gas). Considering the data of hybrid and "plug-in" hybrid vehicles, it is clear that this type of drive is "cleaner" than that used in traditional vehicles. Comparing gasoline-powered vehicles, the difference is approximately 40%, to the advantage of hybrid vehicles. However, it should be emphasized that hybrid vehicles are considered a transitional solution due to the need to continue using fossil fuels. It is worth paying attention to the huge difference in CO_2 production when biofuels (e.g. cellulosic ethanol) are used. Then, when comparing such a hybrid vehicle with a traditional gasoline-powered vehicle, the difference is as much as 84%, to the advantage of the hybrid. The solution that seems to be the most future-proof is vehicles powered by hydrogen cells. Even if hydrogen is obtained from natural gas (after taking into account the carbon dioxide produced during production), its advantage over a traditional vehicle (both gasoline and natural gas) is significant. When compared, their difference is 51% in favour of a hydrogen cell vehicle. Analyzing further data, it is clear that by choosing a more ecological production process, the difference in the level of pollutant emissions becomes huge. In the best case, hydrogen is obtained by electrolysis using energy wind it is as much as 90%.

With the commercialization and spread of hydrogen cell technology, the level of environmental pollution may decrease to a greater extent, because the formation of harmful compounds can only occur at the stage of hydrogen production. When the cell operates in a vehicle or another application, no pollutants are emitted, unlike currently used vehicles and energy sources. For this reason, the increasing number of vehicles will not increase environmental pollution, but on the contrary. In locations with high traffic intensity, there will be a significant decrease in emissions of harmful compounds, which in turn will improve the quality of life, e.g. in large urban agglomerations. Table 5 shows the percentage difference in carbon dioxide emissions for different types of vehicles and fueling methods. The percentages refer to the level of pollutant emissions expected from traditional petrol-powered vehicles achieved according to new emission standards. Negative values express the percentage reduction in emissions compared to a traditional vehicle.

Table 5.
Summary of percentage differences in carbon dioxide emissions depending on the type of drive

	Fuel	**g CO_2/km**	**Difference in emission level, %**
Vehicle power types	Petrol	338	+32,03
Traditional vehicles	Petrol	256	100,00
	Natural gas	200	-21,88
Hybrid vehicles	Petrol	156	-39,06
	Diesel	138	-46,09
	Corn ethanol - E85	119	**-53,52**
	Cellulosic ethanol - E85	41	**-83,98**
Hybrid vehicles plug-in type	Petrol	150	-41,41
	Cellulosic ethanol - E85	94	**-63,28**
Powered vehicles hydrogen cells	H_2 from natural gas	125	**-51,17**
	H_2 from coal	69	**-73,05**
	H_2 from biomass	34	**-86,72**
	H_2 from water electrolysis using wind energy	25	**-90,23**

Source: own based (Sørensen, Spazzafumo, 2018).

4.2. Hydrogen production costs

The production costs of hydrogen obtained from natural gas through steam reforming are known by knowing the input fuel costs. At low pressure (in the pipeline) it is approximately USD 1.0/kg. When filling flasks under pressure, the price is 30% higher, and when liquefying it is more than twice as high. On the other hand, assuming lower transmission volumes, transport costs are lower and by abandoning central hydrogen production, pipeline gas has the highest costs ($5/kg), and based on liquefied gas they are lower ($3.7/kg), depending on assumptions regarding transport distances and technology. It was estimated that obtaining hydrogen from biomass generates a cost of USD 2.5/kg and electricity in the electrolysis process - approximately USD 5/kg. For small electrolysers, the cost of hydrogen has been estimated at USD 8-12/kg, while for larger units using wind energy, the cost decreases to USD 2/kg. In the case of coal gasification, costs exceed USD 12/kg (Tarasov et al., 2021).

In the case of converting excess electricity into hydrogen through a hydrogen cell in a reverse process, but "paid for" by this energy production, and when the costs of the reverse hydrogen cell are similar to that operating in the "one-way", then the cost of hydrogen obtained based on electrolysis in a hydrogen cell may be as low as the cost of the energy used. The energy used for such hydrogen production may be off-peak power or excess power from renewable energy sources such as wind or solar that cannot be used to meet demand at the time of generation.

4.3. Costs of a hydrogen cell

Types of hydrogen cells such as those using molten carbonates or solid oxides are not expected to be in commercial use within the next decade. Initial costs for possible commercialization are estimated at USD 3,200/kW and are expected to drop to USD 1,300/kW in 2050. The problem is the availability of lanthanum (La), used in high-temperature ceramics. Due to previous success, AFC cells are still cheaper than PEM cells, however, both types of cells are still far from meeting all the requirements for large-scale commercial use. The chances of a rapid decline in projected costs for PEM cells do not appear to be equivalent for AFC cells. This fact is explained by the lack of interest in the development of this technology in the future. The costs of a small package of AFC cells are USD 1,750/kW, with the possibility of reducing them to USD 155/kW for large-scale mass production. The costs for a small package of PEM cells are around 2,000 USD/kW, but it is possible to reduce them to USD 20/kW during mass production for the automotive industry (50 kW packages). In 2025, the expected costs are expected to be €30/kW, assuming production of 250,000 units of hydrogen cells per year. The costs of ancillary equipment (gas circulation system, pipes, electronics and electrolyte recirculation system in the case of AFC, and humidifier system in the case of PEM) for PEM cells are estimated to be three times higher than for AFC cells and although they are much lower compared to the cost of the cell, If the price of cells drops, the costs of additional devices may become very significant.

Estimates of profits resulting from the introduction of PEM cells into mass production are determined based on future costs as a function of both the production volume and two parameters: improvement of power density (increase from 2 to 5 kW/m^2) and development speed (taken as the slope of the assumed logarithmic curve cognition (logarithmic learning curve) and are in the range of 15-392 US/kW. The lower cost assumes the appearance of 5 million vehicles powered by hydrogen cells by 2025, with an average power of 110 kW, while the higher one assumes 50,000. vehicles reaching 3 kW/m^2. Vehicles powered by PEM cells are currently designed for a lifespan of approx. 5,000. hours, where, for comparison, stationary generators are designed with a minimum life of 40,000 hours. hours. Current "semi-commercial" vehicles powered by PEM cells do not achieve this level of service life. The estimated cost-effective price for stationary cells by 2025 is $1,200/kW for 5 kW home systems and $700/kW for much larger 250 kW installations (Tarasov et al., 2021). Hydrogen cell units currently being introduced in small series and on a small scale, both in vehicles and in stationary generators used in buildings, may provide a better basis for predicting the possibilities of reducing costs in the future. This could be significant when compared to the learning curves of other energy sector technologies (including wind, photovoltaic energy and battery development). Figure 5 presents the results of the analysis of cognitive curves for wind and photovoltaic technologies.

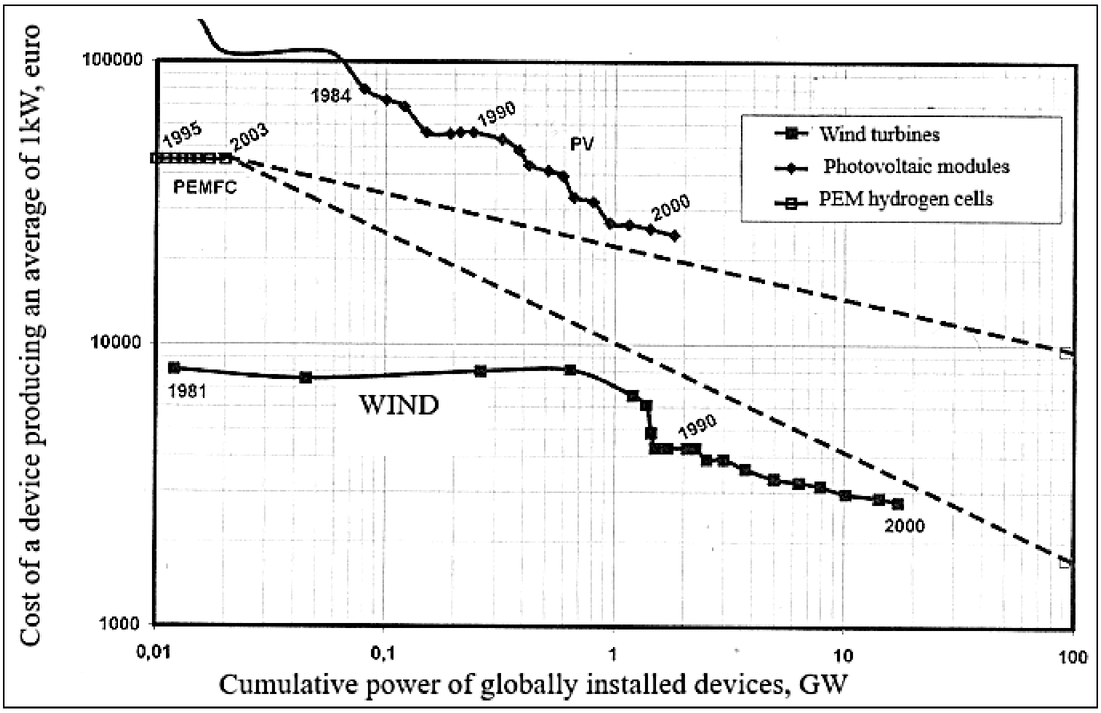


Figure 5. Learning curves for the costs of wind turbines and photovoltaic modules as a possible direction of development of PEM fuel cells.

Source: own-based (Surygała, 2008).

Economists often describe such data as straight-line logarithmic behaviour, describing it as cost 'Y' as a function of cumulative output 'X:

$$\log Y(X) = -r \times \log x + constant \tag{9}$$

Tilt '-r' is sometimes called "progress indicator" (*progress ratio*) $PR = 2^{-r}$ or as a "cognition index" (*learning rate*) $LP = 1 - PR$.

The nature of new technologies does not allow precise determination of initial prices. The reduction in the costs of PEM cells in the future is shown in (Figure 6) in the form of two curves corresponding to 10-20% of the cognitive curves corresponding to photovoltaic modules and wind turbines. However, even for the lower of the curves, the profitability point will not be exceeded if the cumulative energy production does not exceed 500 GW (Tarasov et al., 2021). However, oil market issues could make a hydrogen cell vehicle competitive at a higher price than the break-even point shown in (Figure 6).

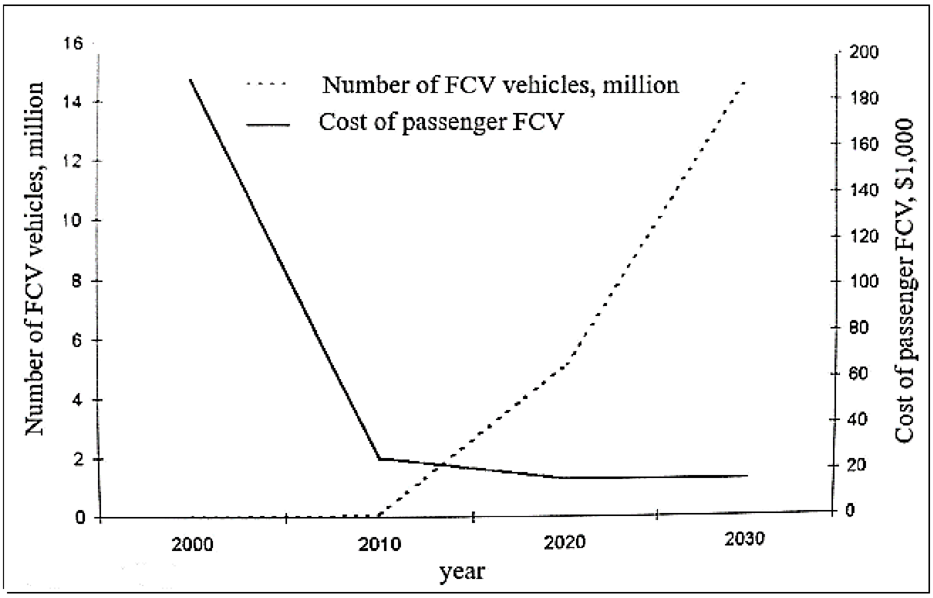


Figure 6. Change in the number and price of FCV vehicles after entering the Japanese market.
Source: own-based (Surygała, 2008).

4.4. Hydrogen storage costs

The costs of hydrogen storage include the costs of using devices and operating costs, including the energy required for compression or condensation. The additional costs of recovering hydrogen from the liquid form are approximately USD 5/kg for small units and approximately USD 1/kg for large units. The additional costs of storing compressed hydrogen in tanks are approximately USD 0.4/kg for short storage times and increase as the storage time increases. Large-scale underground hydrogen storage in caverns, abandoned natural gas wells, aquifers or salt caves have significantly lower costs (total costs of $5-20/kg, making them cheaper by an order of magnitude than storing liquid hydrogen and two orders of sizes below the cost of storing compressed hydrogen), making them a natural choice for central hydrogen storage. Total storage costs for metal hydrides have been estimated at the level of USD 2000-80,000/kg. Storage cycle costs are estimated at USD 0.4-25/kg. This type of storage may be considered for automotive applications, however, the weight will be an issue here except for non-chemical or carbon-based types of storage (Hennig, 2010). Unfortunately, even the best designs have cost several times higher than the costs of storage in pressurized tanks.

4.5. Infrastructure costs

The costs of hydrogen transmission depend on both the diameter of the pipeline and the hydrogen flow rate. By increasing the pressure in the pipeline, the cost can be reduced by more than the additional costs of the compressors. The cost of road transport of liquid hydrogen is estimated to be lower, assuming transport costs for diesel vehicles. However, the additional costs resulting from the need to liquefy hydrogen make this solution unprofitable except in cases of transport over very long distances, e.g. intercontinental using ships. Converting vehicle gas stations into compressed hydrogen refuelling stations may increase the cost of hydrogen by

USD 0.1/kg, but alternatively, hydrogen production can take place at a gas station using any of the available methods (Hennig, 2010). The cost of the required modernization of a gas station so that it can be used for hydrogen refuelling is lower than the annual cost of maintaining a traditional gas station. Using hydrogen production inside a building to power a vehicle parked in a parking lot can double the prices of hydrogen production and refuelling.

4.6. System costs

The costs of a hydrogen cell system are part of the costs of the vehicle and systems installed in buildings and in a broader sense the total cost of the hydrogen economy with production, different types of use and infrastructure such as storage and transmission, distribution and filling points. Research on the PEM hydrogen cell in a car is not only focused on the cell itself but also the costs of the entire car as a system. The total cost of the cell, hydrogen storage, vehicle controllability and traction, battery pack (in the case of a hybrid vehicle) and vehicle energy management are taken into account. All these factors are examined to obtain the total costs incurred by the manufacturer during model development and to subsequently determine the appropriate price level. Studies have shown that the cost of a hydrogen cell will likely fall to $40/kW in 2025 (one of several possibilities) and a corresponding increase in the number of FCVs passenger cars, trucks, buses, etc.) to 15 million in 2030. An increase in demand for vehicles powered by hydrogen cells can be expected as their price decreases. In 2025, the expected price of an FCV vehicle is estimated at approx. PLN 26,000 USD, which is close to the price of current combustion vehicles. Figure 7 shows the demand for hydrogen according to the Japanese scenario along with its costs. And (Figure 8) the number of hydrogen refuelling stations needed and the annual construction costs.

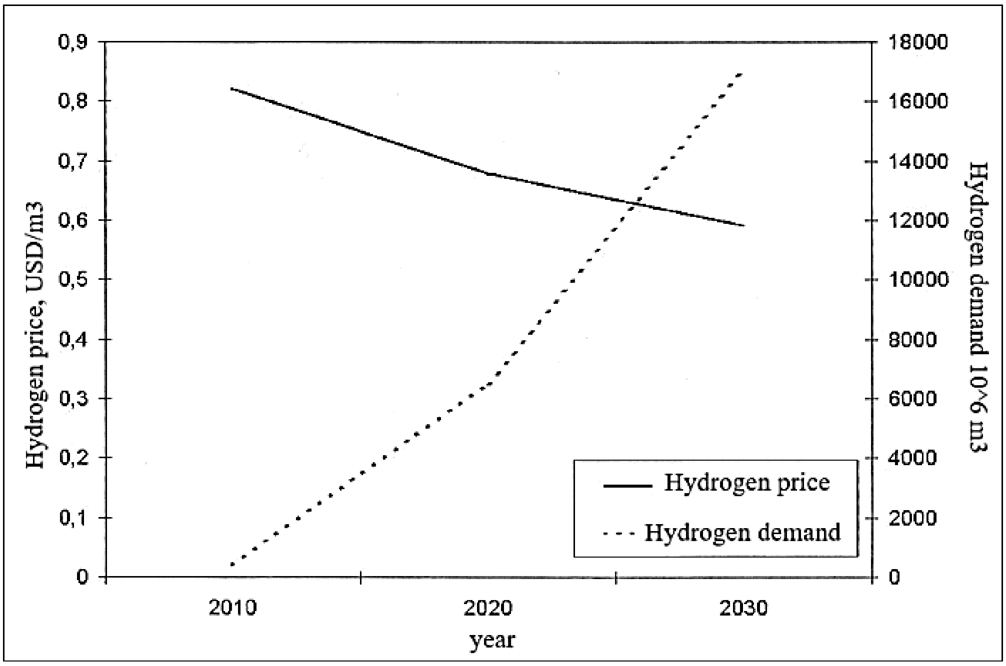


Figure 8. Change in demand and prices of hydrogen according to the Japanese scenario.

Source: own-based (Hennig, 2010) and (Sørensen, Spazzafumo, 2018).

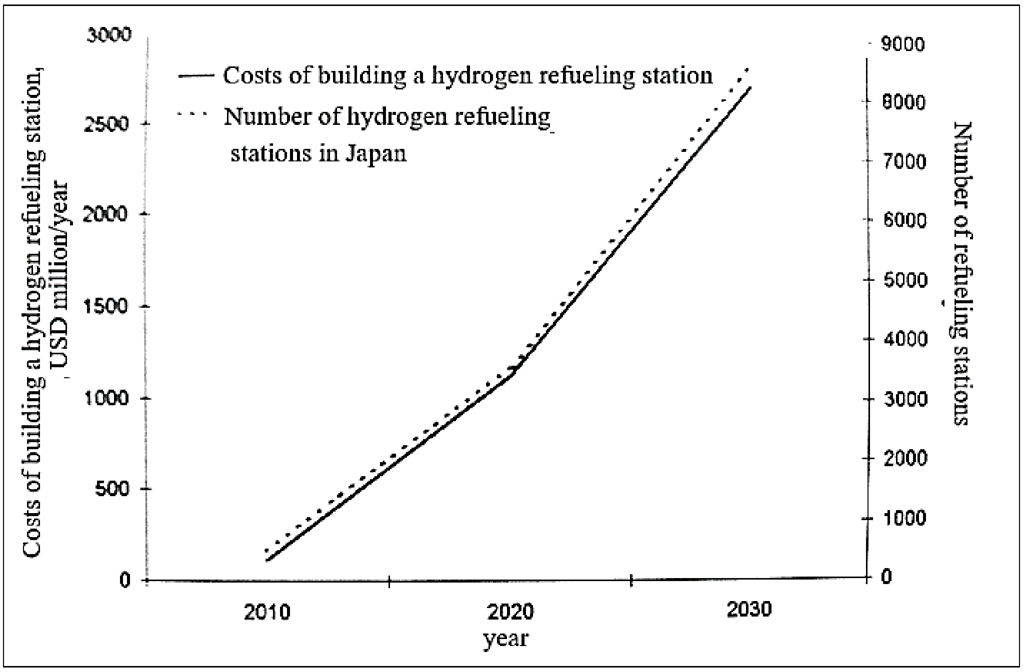


Figure 9. Costs and required number of hydrogen refuelling stations in Japan.

Source: own-based (Hennig, 2010) and (Sørensen and Spazzafumo, 2018).

The scenario assumes a slight population decline in Japan, modest GDP growth and unchanged energy demand. According to the scenario, the production of vehicles with 106 hydrogen cells will increase from 50,000 to in 2010 to 3.1 million in 2030. Such sales in 2030 will allow for sales revenues of USD 59 × USD 109 (assuming that the price of the vehicle includes production costs and a 15% margin) (Hennig, 2010). By 2030, hydrogen-related activities are expected to account for 1% of Japan's total GDP.

5. Summary and Conclusion

Hydrogen cell technology faces many challenges. The very desire to replace conventional ways of powering vehicles or obtaining energy in the global sense in the future is a huge challenge for the entire fuel cell technology. Currently, fuel cells have many problems to solve before they can demonstrate the economic viability of introducing them to society on a global scale. These problems include: include too high costs, the level of reliability and the integration of systems included in cell technology. The level of reliability must be at least at the level of reliability of technologies used for traditional energy production, and the costs must also be comparable. Integrated systems must be able to attract the public's interest in making changes and switching to the new technology.

Cost reduction is essential for fuel cell technology to be successful. Society will not be willing to use new technology when the costs they would have to incur are higher than the costs currently incurred when using current technologies. Although there is a chance that they will be willing to pay slightly more, I think that the degree of "how much more" will depend on the person's awareness of ecological responsibility. For example, until the cost per kW of energy falls, people will continue to use vehicles with traditional internal combustion engines. The main factor limiting the widespread introduction of fuel cells to society is the cost of the fuel fire and the installation costs of the entire system. Both of these costs must be reduced to the level of current energy generation methods. In addition to presenting the use of cells, it is also important to present the level of reliability of fuel cells. It is important to demonstrate that they can provide adequate reliability and quality supplied energy and the possibility of their operation for a long period. Additional factors that would encourage society to switch to the new technology would be subsidy systems for the purchase of fuel cell systems and systems providing benefits from the use of new, pro-ecological technology.

Based on the analysis performed in this work, the following conclusions can be drawn:

1. Due to the increase in energy demand and the prospect of exhaustion of fossil fuel resources, there is a need to develop a new energy source. Rising fuel prices will lead to a reduction in their availability to society, and at some point, they will cease to be a profitable source of energy.
2. The increase in energy consumption and the number of vehicles causes a global increase in pollution and requires the spread of "clean" energy sources. The analysis carried out on the example of the automotive industry showed the possibility of a significant reduction in pollutant emissions as a result of replacing conventional methods of powering vehicles with hydrogen cells.
3. The possibility of obtaining hydrogen from various sources allows us to become independent from fossil fuels. Moreover, hydrogen as a fuel is safer than conventional fuels due to its physical and chemical properties.
4. The multitude of developed types of hydrogen cells allows for their optimal adaptation to applications and working conditions. Thanks to this, it is possible to expand the range of available applications and adapt to the user's convenience.
5. Despite the promising parameters of hydrogen cells, it is currently not possible to use them in commercial applications. To successfully implement them, there must be a reduction in the costs of technology, fuel, use, improvement of operating parameters and an increase in the availability of devices and vehicles, as well as the related infrastructure.
6. It is necessary to introduce government programs encouraging society to use hydrogen cell technology. A useful tool in this case would be tax relief or financing of part of the costs addressed to private individuals and companies willing to use fuel cell technology.

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