The use of fuel cell technology as electricity and heat generators in residential buildings

Wykorzystanie technologii ogniw paliwowych jako generatorów energii elektrycznej i ciepła w obiektach mieszkalnych

RENATA WŁODARCZYK

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Guided by the assumptions resulting from the Polish Energy Policy until 2040 and the Act on electromobility, hydrogen may become an attractive form of long-term storage of electricity in the future. The article presents the possibilities of using fuel cell technology to generate heat and electricity. The principle of operation of a hydrogen cell was characterized. Existing solutions and trends in the development of this technology were presented. In addition, the financial and technological aspects of fuel cell technology were assessed. The use of fuel cells in a hybrid system is an effective way of storing electricity. Energy storage in the form of hydrogen is a new trend resulting from the advantages of generators converting energy stored in hydrogen, i.e. in fuel cells. Combustion of hydrogen in fuel cells does not emit any toxic gases, the efficiency of this process reaches 85%, the cells have a modular structure, their operation is noiseless and vibration-free.
Keywords: fuel cells, hydrogen energy generator, CHP generator, emergency systems, hydrogen stations

Kierując się założeniami wynikającymi z Polityki energetycznej Polski do 2040 roku oraz Ustawą o elektromobilności, wodór może stać się w przyszłości atrakcyjną formą długotrwałego magazynowania energii elektrycznej. W artykule przedstawiono możliwości zastosowania technologii ogniw paliwowych do generowania energii elektrycznej i ciepła. Scharakteryzowano zasadę działania ogniwa wodorowego. Przedstawiono istniejące rozwiązania oraz trendy rozwoju tej technologii. Ponadto dokonano oceny technologii ogniw paliwowych w aspekcie finansowym i technologicznym. Wykorzystanie ogniw paliwowych w układzie hybrydowym stanowi efektywny sposób magazynowania energii elektrycznej. Magazynowanie energii w postaci wodoru jest nowym trendem wynikającym z zalet, jakimi charakteryzują się generatory przetwarzające energię zmagazynowaną w wodorze to jest w ogniwach paliwowych. Spalanie wodoru w ogniwach paliwowych nie emituje żadnych toksycznych gazów, sprawność tego procesu dochodzi do 85%, ogniwa mają budowę modułową, ich praca jest bezgłośna oraz bezdrganiowa.
Słowa kluczowe: ogniwa paliwowe, wodorowy generator energii, generator CHP, systemy awaryjne, stacje wodorowe

Introduction

Due to the exhausting resources of fossil fuels and the need to search for new energy carriers, it is worth paying special attention to the alternative fuel, which is hydrogen. The production of hydrogen requires the use of energy. Renewable energy sources may be the answer to this problem. Construction of hybrid systems, in which the main device is a fuel cell producing electricity and heat directly in buildings without pollution and with much lower greenhouse gas emissions, becomes an alternative to boilers, internal combustion engines as part of microgeneration systems.

When assessing the current state of development of fuel cell technology, one should be aware of the existing technological, economic and legal barriers that must be overcome in order for this technology to become available to commercial customers. On the other hand, numerous studies and pilot programs show that commercialization of fuel cell technology is only a matter of time. All the premises (high prices of CO_2 emission allowances, growing demand for electricity, increasing environmental pollution, depleting fossil fuels) indicate that in the near future there will be an increase in the intensity of the development of hydrogen technologies along with the issue of using hydrogen as an energy carrier.

According to the draft document "Poland's energy policy until 2040" one of the priority directions of the Polish energy policy is to increase the security of fuel and energy supplies [1-2]. The main goals and directions contained in this document relate indirectly to hydrogen storage and concern:

- improvement of energy efficiency,
- development of the use of renewable energy sources,
- limiting the impact of the energy sector on the environment.

Provisions included in the "Polish Energy Policy until 2040" are in line with EU action and hence with a strategy to transform into a low-emission economy or even to operate in an environmentally neutral way. The listed man activities and specific objectives are to radically reduce the energy consumption of the Polish economy, as well as households. The global energy and climate policy forces us to look for alternative solutions and sources of cheap electricity. The Ministry of Climate is working on the development of the Polish

Dr inż. Renata Włodarczyk https://orcid.org/ 0000-0002-0093-5178 - Department of Energy Engineering, Faculty of Infrastructure and Environment, Czestochowa University of Technology, J.H. Dabrowskiego Str. 69, 42-201 Czestochowa. Corresponding Author: renata.wlodarczyk@pcz.pl

Hydrogen Strategy until 2030. In autumn 2020, the text of the strategy was submitted for public consultation. According to the assumptions, the development of the hydrogen sector is to contribute to the reduction of greenhouse gas emissions by Poland, as well as other pollutants into the atmosphere. The reduction of pollutant emissions is to concern mainly the transport sector. The development of the power-togas technology is expected to significantly increase the consumption of hydrogen in heating. The development of this sector is to increase the share of hydrogen in the structure of energy fuels, and thus reduce the import of energy resources. An important goal of the actions taken is to increase Poland's energy security and increase independence from foreign suppliers. Important goals of the hydrogen strategy developed in Poland include, inter alia, [3]:

- creating a value chain for low carbon hydrogen technologies;
- implementation of hydrogen as a transport fuel;
- preparation of new regulations for the hydrogen market;
- strengthening the role of hydrogen in building Polish energy security.

On July 8, 2020, the European Commission announced two documents regarding energy policy. These documents are in line with the principles of the European Green Deal. One of them is the Hydrogen Strategy, and the other one concerns the connection of the transport, heating and electrification sectors, and the promotion of clean fuels [4]. Renewable gases, referred to as "green", including hydrogen, are to play a key role in the EU's energy policy. This gas can be used as a fuel, raw material, energy storage in various branches of the economy, including transport, industry, construction and energy. During use, hydrogen does not emit any pollutants, including carbon dioxide. It is therefore an alternative to the decarbonisation of industrial processes. Therefore, its production should be increased. While the number of companies belonging to the International Hydrogen Council in 2017 was 17, by mid-2020 it was already 81. According to the EC's plan, by 2030: construction of electrolysers with a capacity of 8.2 GW (57% in Europe). The share of hydrogen in Europe's energy mix will amount to 13-14% in 2050.

It is planned to obtain hydrogen from conventional, renewable and nuclear fuels. The vast majority of hydrogen production consists in splitting water by electrolysis of water, steam, electrochemical decomposition of water, photolysis, thermal or biological fission. The priority is to develop hydrogen production from renewable sources, especially from solar energy and wind. These are the cleanest methods of obtaining hydrogen. By 2050, the cost of obtaining hydrogen from renewable sources is expected to decrease, which will result from the development of new technologies. Hydrogen can also be produced from biogas or biomass reforming.

Construction and operation of PEMFC fuel cells

Currently, many research centers are involved in research on fuel cells by extending the working time of the cells, reducing the weight of the tooling, or reducing the costs of the cell production itself [5-6]. The operation of a fuel cell is based on generating electricity resulting from the oxidation reaction of the supplied fuel. The only limit to the amount of energy a cell can produce is the capacity of the fuel tank. Most fuel cells for the production of electricity use the hydrogen oxidation reaction at the anode and the reduction of oxygen at the cathode (fuel cells with an electrolyte in the form of a polymer membrane - Polymer Exchange Membrane Fuel Cells - PEMFC) [7].

The driving force in a fuel cell is the natural tendency of the system to achieve a state with a lower free enthalpy. Hydrogen and oxygen are unstable as a mixture and form water spontaneously. Due to the almost trace amounts of pollutants produced (exhaust gas consists only of water vapor that is harmless to the natural environment) and high efficiency (chemical energy is directly converted into electricity, efficiency is not limited by Carnot), fuel cells have become the focus of attention of many scientific enters.

The wide application and use of fuel cells as the primary power source, among others in vehicles, emergency power systems or in the energy sector, may significantly reduce the effects of global warming, the problem of our century, in the perspective of several decades [8-10]. The structure of a fuel cell is based on two electrodes separated by an electrolyte. The electrochemical oxidation of the fuel takes place at the anode, while the oxidant is reduced at the cathode. As a result of electrochemical processes, a potential difference is created between the cathode and anode, and an electric current flows in the external circuit. By-products are water and heat. In this way, the cell becomes an electricity generator. The construction of a single hydrogen fuel cell and the principle of operation are shown in Fig. 1.

From two hydrogen molecules, four protons and four electrons are made, according to the equation (1) [7]:

$$2H_2 \rightarrow 4H^+ + 4e^- \qquad (1)$$

The electrons formed in this way, as they travel towards the cathode through the external electrical circuit, cause a current to flow that is fed to the receivers. Protons, on the other hand, diffuse through the electrolyte. The proton-exchange membrane conducts only protons, preventing the migration of other ions, especially oxygen ions coming from the cathode. At the cathode, oxygen reacts with the electrons to form anions O^{2-} (2):

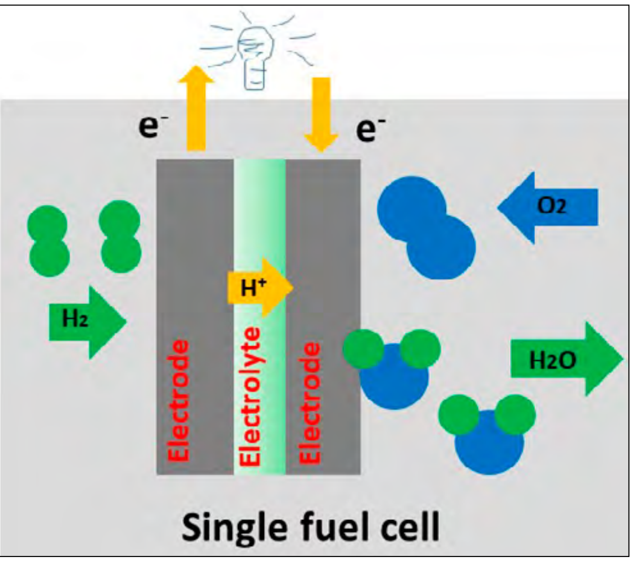
$$O_2 + 4e^- \rightarrow 2O^{2-} \qquad (2)$$

On the other hand, the H + protons are neutralized with ionized oxygen (3):

$$2O^{2-} + 4H^+ \rightarrow 2H_2O \qquad (3)$$

The end product of the cell's operation is H_2O in liquid or gas form.

Fig. 1.
Single cell of PEMFC [7]
Rys. 1. Schemat pojedynczej celi ogniwa typu PEMFC [7]



The generator based on fuel cell technology is characterized by the following features [8-9]:

– the hydrogen fuel cell produces no local pollutants, water vapor is a by-product;
– energy in cells is produced with high efficiency, which additionally does not depend on the dimensions of the device;
– cells can work in modular systems; to increase the amount of energy produced, it is enough to connect subsequent packages (cells) to the cell;
– the work of the cell is noiseless, only the work of auxiliary devices can be heard;
– operation in a fuel cell can be continuous as long as fuel and oxidant are supplied continuously,
– the cell automatically selects the fuel and regulates the appropriate amount of oxidant;
– thanks to the use of a solid electrolyte cell, the system can operate in difficult operating conditions, the cell's operating time is currently 10 years of continuous operation [9],
– the location of small generators in the vicinity of energy consumers allows them to additionally use the waste heat for space heating, water heating and absorption cooling, which can increase the efficiency of using natural fuels by up to 80%.

The idea of using hydrogen fuel cells

Fig. 2 shows a diagram of the use of fuel cells in a hybrid system with the use of renewable sources [5]. Combining hydrogen cells with photovoltaic panels in a hybrid system makes it possible to store hydrogen, which is produced in the electrolyser thanks to the surplus energy produced from solar energy. The electrolyser and the hydrogen storage are two elements that enable the cooperation of both technologies. The cooperation of hydrogen fuel cells with generators processing renewable energy sources (in this case with photovoltaic panels) is beneficial due to the fact that both technologies complement each other. The photovoltaic installation produces electricity, and its surplus can be sent to an electrolyser, which, using recycled water from the cell and electricity from renewable energy sources, produces high-purity hydrogen - 99.999%. Hydrogen can be directly sent to a hydrogen generator or stored in special cylinders. In this way, fuel cells can replace photovoltaic panels in times of high cloudiness or at night. The most advantageous solution in the hybrid system in question is the design of the installation, along with the selection of appropriate generators processing renewable energy sources, so that the largest possible part of the electricity demand for hydrogen production and utility needs is covered directly by the installation itself, based solely on renewable energy sources, producing green hydrogen [11-12].

There are many innovative solutions for the use of fuel cells in cooperation with generators processing renewable energy sources, but it can be noticed that these installations are structurally similar in many elements and are based on hydrogen cells, and differ only in the way they are used [13]. The proposed solutions are used in areas such as: transport, industry, housing, energy storage [14-15].

The production of hydrogen by electrolysis is expensive, but the economies of scale will reduce the costs of generating electricity, hydrogen and the necessary equipment. The proposed hybrid technology allows us to become independent from fossil fuels. The use of hydrogen as an energy carrier, or energy storage, can be a significant support for conventional and unconventional power plants in periods when there are excess electricity production (periods of hydrogen production from surpluses) or its shortages (use of hydrogen for energy production). The proposed hybrid system is a system that can be both an energy producer and its recipient. The use of the generated heat during the operation of hydrogen cells allows to further improve the efficiency of the entire system.

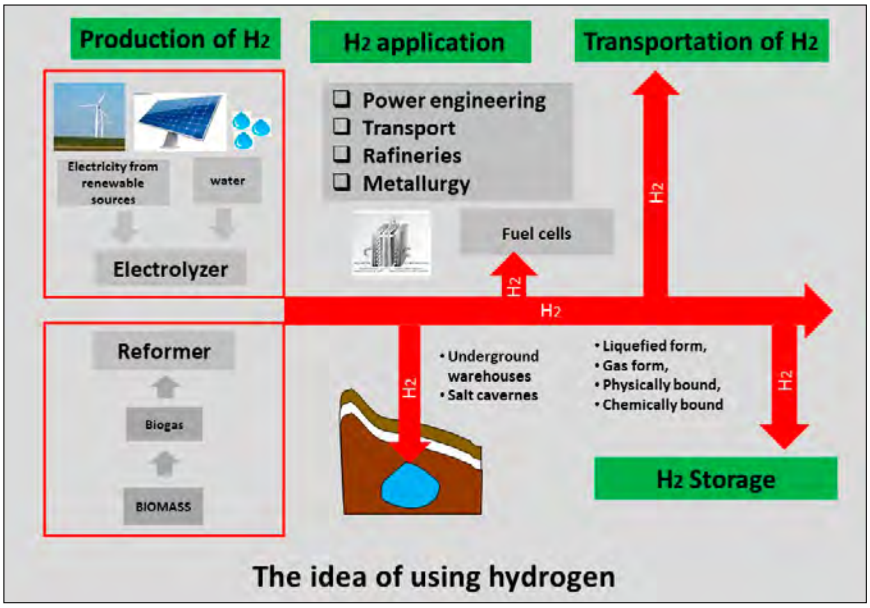


Fig. 2.
Example of a hybrid system fuel cell + photovoltaic cell + electrolyser [16]
Rys. 2. Przykład systemu hybrydowego ogniwo paliwowe + ogniwo fotowoltaiczne + elektrolizer [16]

The value chain of hydrogen as an energy carrier

Currently, hydrogen is used mainly in fuel cells, in the chemical industry for the synthesis of methanol and ammonia. The main advantage of hydrogen cells when using hydrogen as fuel is the lack of emissions to the environment, but the disadvantage of having to produce it, which requires energy expenditure. The advantage is that their operation does not depend on weather conditions, but only on the availability of fuel. Fuel cells are able to react quickly to the changing load in the network through the appropriate consumption of hydrogen. In order to accelerate the reactions taking place on the electrodes, the use of appropriate catalysts, most often platinum, is required, which increases their price. Fig. 3 shows the hydrogen value chain from the moment it is obtained, prepared as fuel, through the possibilities of its storage and use, especially in the power industry and industry.

Methods of obtaining hydrogen

The methods of obtaining H_2 can be further divided into the following processes:

– biological: they do not require the use of high temperatures and pressures, they occur under ambient conditions, therefore they are expected to be less energy-consuming than thermochemical methods of hydrogen production [17]. The most ecological way of producing hydrogen is a photobiological process which uses biomass and waste, algae and enzymes, bacteria and fungi.
– thermal: these include steam reforming, gasification, thermal decomposition of water [18]. When using fossil

fuels, processes such as steam reforming and thermal cracking of natural gas, coal gasification, partial oxidation of heavy hydrocarbons are used. When using biomass as a raw material for the production of hydrogen, the pyrolysis or gasification processes of biomass are used, in which the products are a mixture of hydrogen, methane, oxygen carbon compounds and nitrogen.
– electrochemical: decomposition of water under the influence of electric current - electrolysis and under the influence of solar radiation - photolysis.

Hydrogen storage and transport

The most popular method is hydrogen gas storage [19]. For this purpose, metal or composite tanks are used, in which hydrogen compressed to higher pressures (35 - 70 MPa) can be stored. Hydrogen can be stored in pressurized tanks in stationary systems (hydrogen for use in laboratory conditions, for research centers, skin clinics, in diagnostics, etc.) or in mobile systems (hydrogen for the automotive industry, where it is used to drive vehicles). Stationary storage tanks are most often made of steel and hydrogen is forced in at a pressure of 15-20MPa. These tanks, due to their weight, are not used in mobile systems. In this case, containers made of composite materials, double and triple-walled: aluminum tanks covered with composite fibers, with an outer jacket made of epoxy resins [20].

Underground energy storage in the form of Hydrogen (Hydrogen Underground Storage) is a potential solution to the problems of energy storage. This technology is part of the energy cycle: energy production conversion to hydrogen hydrogen storage conversion of hydrogen into other types of energy energy consumption. The use of geological structures makes it possible to store hydrogen, which, as energy is required, is released into the network during peak hours. Several options for storing hydrogen are considered with the use of geological structures such as: salt caverns, used hydrocarbon deposits, deep aquifers [21-22]. Geological structures can ensure the safe storage of large amounts of hydrogen. Hydrogen stored in geological structures does not require special cylinders, and the lack of contact with atmospheric oxygen reduces the risk of creating an explosive mixture. Storage of energy in hydrogen is a good way to prevent interruptions in electricity supply in a crisis moment, e.g. when high temperatures threaten the stable operation of conventional power plants, causing a reduction in their efficiency, and therefore there is a risk of black-out. Storing energy in hydrogen only makes sense if:
– the energy needed to produce it comes from renewable energy sources, as electricity is still generated without polluting the environment.
– economies of scale make this production profitable.

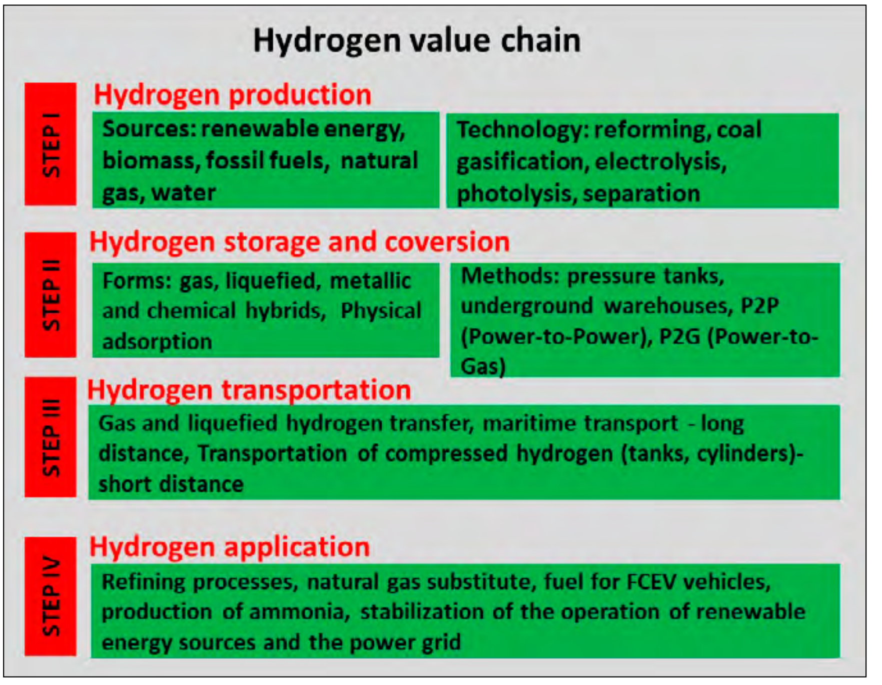


Fig. 3.
Hydrogen value chain [23]
Rys 3. Łańcuch wartości wodoru [23]

Fuel cells as CHP generators

CHP generators (acronym Combined Heat and Power) can work as primary energy sources, energy sources connected to the grid and as UPS devices. Due to the lack of a hydrogen infrastructure, CHP generators are often adapted to run on natural gas. However, in this case, the generators use high-temperature fuel cells that allow internal reforming of the gas to obtain hydrogen, or it is necessary to use the so-called fuel processor that produces hydrogen from natural gas [24]. The use of a high-temperature fuel cell is associated with a reduction in the speed of the generator's response to load changes and an extension of the start-up time, which requires the construction of a more complex energy modeling system. In turn, the use of a fuel processor increases the cost of the generator and reduces its efficiency (due to the additional amount of energy required by the fuel processor). The optimal solution is to use a generator generating energy directly from pure hydrogen [25]. Then there is no local production of carbon compounds, the generator does not require the implementation of additional equipment, which makes the construction simpler, while reducing the price of the generator. The obstacle is the lack of a hydrogen infrastructure and the need to store hydrogen in the tank, which limits the possibility of continuous operation of the generator. The fact of the increasing level of electricity consumption in the household results from the increasing importance of electrically powered devices in everyday life and the rapid spread of new electrical devices on the market. With the limited potential of fossil fuels, it becomes important to reduce electricity consumption through the production of energy-saving electrical devices and the implementation of new, efficient, alternative energy sources. Fuel cells can significantly contribute to solving the above-mentioned problems [26-27]. The large-scale use of hydrogen-based generators will allow the power grid to be decentralized, which will contribute to better use of energy resources through high efficiency and minimizing losses resulting from long-distance energy transmission. Taking into account the efficiency of CHP in generating electricity and heat, economic analyzes and analyzes of energy demand for single-family houses constituting a potential source of demand for generators using fuel cells for energy generation were carried out. Assuming that the house was built according to currently applicable thermal insulation standards, it can be assumed that an energy of 50 (kWh /m^2) / year is required for heating. Assuming the average annual CHP efficiency of 50%, we obtain the value of 50/0.5 = 100 kWh /m^2 per year. A CHP generator with an electric power of 16 kW and an efficiency of 60% (10 kW of thermal power) is able to provide enough electricity for a single-family house [28].

Trends in the production of CHP generators based on fuel cell technology define their future application:

– small and medium power plants up to several MW - solutions dedicated to several farms ensuring high operational efficiency,
– UPS generators as replacements for combustion generators (used e.g. in hospitals) and generators based on conventional batteries / accumulators,
– parallel CHP generators connected to the network / UPS,
– hybrid systems in which CHP generators can cooperate with other energy sources, e.g. photovoltaic cells, gas turbines.

Hybrid systems can work as systems using renewable energy sources (RES), as well as conventional methods of electricity conversion, further as devices for energy storage and "storage" and complex supervision and control systems. The energy hidden in RES is a great potential, but at the same time creates considerable problems with the irregularity / periodicity of its occurrence. An interesting way to minimize the presented problems is to combine devices into entire systems, compensating for each other's drawbacks. The purpose of such systems is to maximize the use of solar and wind energy during periods of low solar radiation or windless days. The use of photovoltaic panel - fuel cell or wind turbine - fuel cell systems increases the efficiency of energy conversion of the entire system. According to the definition contained in the Regulation of the Minister of Economy, a hybrid system is [29]: a generating unit generating electricity or electricity and heat, in which energy or heat production uses energy carriers that are produced separately in renewable energy sources and in other energy sources than renewable and consumed jointly in this generating unit to generate electricity or heat. Installing hybrid generation systems (HSW) is advantageous especially where the lack of power grids, mainly in remote locations, when the transport of fuel to conventional generators is difficult. Installations of this type are expensive. Their high price is due to the necessity to oversize their devices and the necessity to use energy accumulators. CHP generators based on fuel cell technology are the subject of research and work by many technologically advanced companies. Among the different types of microcogeneration systems, cogeneration systems using fuel cells can achieve 90% efficiency (60% for electricity and the rest for heat). Their low heat-to-power ratio means that they fit perfectly into the increasingly common home trend, which is characterized by higher electricity consumption and a low demand for space heating. Despite the high potential for domestic applications, microgeneration systems have not yet reached the commercial stage. Also in Poland, steps were taken to construct a CHP generator designed to generate electricity and heat in single-family houses.

Global solutions for the use of fuel cell technology

Considering the size of the installation, the market for stationary fuel cells for gas power applications can be divided into two categories:

– low electric power cells for domestic applications (from 0.5 to 10 kW),
– large cell installations with an electrical capacity of up to several MW. In the first group, there are approx. 80 manufacturers who offer pre-commercial and test systems of polymer fuel cells PEMFC - (approx. 85% market share) and oxide – SOFC [30]. In order to review the producers of fuel cells used as stationary generators in cogeneration systems, a report prepared in 2019 by the European Commission was used [30]. Overall figures show that the deployment of fuel cell systems is region-dependent, including the presence of producers and end--users who need a steady supply of electricity in regions with poor grid reliability. The decisive factor influencing the implementation process of fuel cell generators is the cost to be paid for energy by the user. This value depends on the efficiency of the technology, maintenance and operating costs, reliability and service life.

Natural gas (about 50%) and hydrogen (about 45%) dominate in powering this type of fuel cells. The high proportion of hydrogen applies mainly to cells operating periodically. The market of large installations is dominated by several producers, but the pace of its development is slower due to the necessary large financial outlays for research and a high degree of technological complexity.

Examples of selected investments using fuel cells as micro-power plants are presented in Table 1 [30-32].

There are many examples of the use of renewable energy sources in cogeneration

Table 1. Fuel cells as electricity and heat generators – selected investments
Tabela 1. Ogniwa paliwowe jako generatory energii elektrycznej i ciepła – wybrane inwestycje

Type of fuel cell/power	Company/country	Application details
PEMFC 4,6 kW	Vaillant GmbH (Germany)	Low-power cells as home CHP
do 10kW	EFOY (US)	
SOFC 1 kW	Hexis AG (Switzerland)	
Do 250 kW	firma UTC Power (US) MTU CFC Solutions (Germany), Siemens Westingouse (US),	Commercial and pre-commercial phase for large installations
1.4 MW fuel cell installations	FuelCell Energy for Pepperidge Farm Company w Bloomfield, Connecticut- 2016	
two blocks with a capacity of 5.6 MW	FuelCell Energy for Pfizer Inc. w Groton, Connecticut.	
fuel cell park with a capacity of 20 MW	FuelCell Energy for Korea Southern Power Co. Ltd. (KOSPO)- 2018	The cell park of eight SureSource 3000 plants.
The plant consists of 440 kW PAFC cells with a capacity of approx. 50.16 MW.	Daesan Hydrogen Fuel Cell Power Plant in Seosan, South Korea - 2020	Stationary installation of fuel cells, the investment will provide 400,000 Mwheels per year, to power 160,000 homes.
Installation with a capacity of 59 MW	FuelCell Energy from Danbury Conn in the city of Hwasung Gyeonggi Green Energy operates in South Korea - 2014	The installation consists of 21 hydrogen fuel cell
Installation with a capacity of 19.6 MW. The output power is sufficient to power approximately 45,000 South Korean households.	Godeok Park located in Seoul	The plant consists of seven DFC3000 fuel cell power plants, each providing 2.8 MW of power
	After the accident in Fukushima, a microgeneration fuel cell installation for households was built as part of the Ene-Farm project	Between 2009 and 2016, 150,000 fuel-cell micro-CHP plants were installed in Japan.

with the production of hydrogen for fuel cells, both in Europe and in the world. Here are just a few of them:

- HDF Energy [34] power plant in French Guiana commissioned in 2020, a system consisting of an energy storage unit combining photovoltaic panels and hydrogen cells. The power plant consists of a solar farm with a capacity of 55 MW and an energy storage with a capacity of 140 MWh. The surplus from the photovoltaic electricity production is used to generate hydrogen through the electrolysis process. This project assumes a stable electricity supply for 10,000 households. During the day, the power plant is to provide a target of 10 MW of power, and 3 MW at night.
- A power plant built in the Solway company (Lillo near Athens, Belgium) with a capacity of 1MW, built in 2012 [31]. It has a power unit consisting of fuel cells with a total capacity of 1 MW. The plant is housed in a container and the hydrogen is obtained from chemical plants producing chlorine, where the hydrogen is a by-product.
- The Green Flamingo project was realized in Portugal, solar energy produced on a 42 hectare solar parlor in the hinterland of the Algarve region of Portugal is used to profitably produce hydrogen from seawater. Since drinking water in Portugal is difficult to obtain, ocean access and water desalination are essential. The production of one cubic meter of hydrogen requires about six liters of water [32].
- In Australia, a solar energy project is under construction, including a 14 GW solar farm and a 30 GW energy storage. The installation will be built in Australia's Northern Territory near Tennant Creek. The solar farm will cover an area of 12 thousand square meters. ha at Powell Creek station [33].
- On the island of Kaua'i, photovoltaic power plants are being built with a capacity of several dozen MW, satisfying about 17.5 percent the island's energy needs. Works there include a 14 MW photovoltaic farm built by SolarCity, a company associated with Elon Musk. Now SolarCity will build on this island more photovoltaic farms with energy storage [34].

Currently, fuel cell technology is on the verge of commercialization, the development of this technology is very dynamic, its commercialization is expected for the next 10 years. However, the price of cells remains high, which is due to the small number of companies involved in the production of cells and the early stage development of this technology. Large research expenditure contributes to the rapid increase in the quality of fuel cells, but generates a high price. The trend of fuel cell costs is declining, a kilowatt of energy in the fuel cell used in the Apollo space program (1970) cost $ 600,000 / kW, while today the cost of a kilowatt is from $ 1,500 / kW. For comparison, the cost of 1 kW of power for a combustion generator is $ 800 - $ 1500 / kW, and for a gas turbine - $ 400 or less [35].

According to data posted on the US Department of Energy's website, research funding for fuel cell technology to increase efficiency while reducing the cost of cells is very large, amounting to $ 1.2 billion over the next 5 years [36]. The goal is to achieve a price of $ 400 / kW in 2022 with a cell efficiency of over 40% (in electricity generation) [37-39]. Similar scientific and research programs are also financed in other highly developed countries. The leader in the implementation of fuel cells and research works is Japan, where CHP generators already produce electricity today and heat in homes [40].

Summary

The assumptions of the most important legal acts concerning the hydrogen policy and hydrogen technologies indicate the priority aspects that should be developed in order to meet international requirements. These include the storage and transport of hydrogen on an industrial scale and the optimization of the process of its production. Fuel cells have already entered the path of commercialization on the world market, so the processes of using hydrogen to produce electricity in these generators are already known.

However, the challenge is to develop a technology for storing hydrogen. The solutions for storing hydrogen in cylinders (in liquid and gas form), chemically and physically bound, make it possible to transport and eliminate the risk of gas explosion and flammability. Poland also has the potential to store hydrogen in underground storages in places with a characteristic geological structure (salt caverns, exhausted oil and gas deposits, deep aquifers). Backup power is likely to be the most promising market for fuel cells in the near future, followed by portable, stationary and transport generators. For stationary and transport purposes, the most popular will be the cheap unit with stable catalysts with polymer membranes. Energy storage in the form of PEM type cells may be able to protect power networks in times of failure and enable power plants to operate with a constant load by covering the increased demand for electricity.

The potential of hydrogen has been appreciated by the largest energy and refining companies, which will undoubtedly result in the development of hydrogen technology in Poland. Today's legal and research needs for the broadly understood hydrogen economy concern the following research areas:

- development of strategic documents for the implementation of hydrogen-based technology;
- developing procedures of conduct for emergency services during crisis situations;
- development of hydrogen storage methods in terms of application in transport and creating a safe transmission network;
- diversification of sources of obtaining hydrogen in order to obtain a hydrogen price comparable to the price of fossil fuels;
- energetic use of hydrogen in fuel cells for highly efficient electricity generation.

It is estimated that the implemented investments related to green hydrogen (obtained from RES), supporting the "hydrogen revolution", will amount to 180 to 470 billion euro by the end of the planned Strategy [41]. These funds will be allocated, inter alia, to the expansion of solar and wind energy equipment, the expansion of the transmission network, the modernization of hydrogen production plants, and the creation of infrastructure for storage, distribution and transport of hydrogen. The implementation of the Strategy is supported by the European Clean Hydrogen Alliance, which brings together representatives of civil society, industry, administration, and the European Investment Bank (EIB). An important instrument is the Next Generation EU, which is expected to double its capabilities. Its role is to support private investment in disseminating the hydrogen market. The green transformation is supported by the European Regional Development Fund and the Cohesion Fund in supporting innovative solutions in the field of low-carbon and renewable hydrogen, as well as technology transfer. Funds will be allocated to testing new projects, solutions, activities related to increasing hydrogen demand, creating new markets an outlet for hydrogen.

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REFERENCES

[1] Polityka Energetyczna Polski do 2040 roku (PEP 2040) (in Polish), https://www.gov.pl/documents/33372/436746/PEP2040_projekt_v12_2018-11-23.pdf/ee3374f4-10c3-5ad8-1843-f58dae119936 (accessed on 22 April 2021).

[2] Krajowy plan na rzecz energii i klimatu https://bip.mos.gov.pl/index.php?id=5608 (accessed on April 2021).

[3] https://energetyka24.com/polska-pracuje-nad-strategia-wodorowa-bedziemy-musieli-znalezc-swoja-nisze (accessed on 22 April 2021).

[4] A hydrogen strategy for a climate-neutral Europe, Komunikat Komisji do Europejskiego Parlamentu, Bruksela 8 lipca 2020 r (accessed on May 2021).

[5] Navas-Anquita Z, Garcia-Gusano D., Dufour J., Iribarren D., Applied Energy, 259, 2020, 1-11.

[6] Lotric A., Sekavcnik M., Kustrin I., Mori M., Int. J. Hydrogen Energy, 46, 2021, 10143-10160.

[7] Wlodarczyk R., Research on the functional properties of materials used for PEMFC fuel cell interconnectors, Publisher Czestochowa University of Technology, Czestochowa, 2011.

[8] Mustain W.E., Chetenet M., Page M., Kim Y.S., Royal Society of Chemistry, 13, 2020, 2805-2838.

[9] Thompson S. T., Peterson D., Ho D. , Papageorgopoulos D., J. Electrochem. Soc., 167, 2020, 084514.

[10] Skorek A., Dreksler M., Włodarczyk R., Wodór jako współczesny nośnik energii, Monografia: Ograniczanie emisji CO2 – przeciwdziałanie zmianom klimatu", Politechnika Częstochowska, Seria Monografie 308, 2015, 84-97, ISBN 978-83-7193-646-X, ISSN 0860-5017.

[11] Au S.F., Hermes K., Woudstre N., Journal of Electrochemical Society, 2002, 149, 879-885

[12] International Energy Agency, Hydrogen Production and Storage, https://www.iea.org/publications/freepublications/publication/hydrogen.pdf, (accessed on 22 April 2021).

[13] Demusiak G., Otrzymywanie paliwa wodorowego metodą reformowania gazu ziemnego dla ogniw paliwowych małej mocy, Nafta-Gaz, Państwowy Instytut Badawczy, 2012.

[14] Demusiak G., Warowny W., Gaz Woda i Technika Sanitarna, 10, 2005, 10–15.

[15] Melis A. Int. J. Hydrog. Energy, 27, 2002, 1217–1228.

[16] Włodarczyk R., Kacprzak A., Magazynowanie energii w postaci wodoru w warunkach polskich - potencjał i wyzwania (w:) Nowoczesne technologie konwersji i magazynowania energii, Politechnika Częstochowska, 2019, 138-165, ISBN 978-83-7193-721-7

[17] Rozendal R.A., Hamelers H.V.M., Euvernik G.J.W., Metz S.J., Buisman C.J.N., Int. J. Hydrogen Energy, 31, 2006, 1632-1640.

[18] Alptekin G., De Voss S., Dubovik M., Monroe J., Amal-fitano R., Israelson G. J. Materials Engineering and Performance, 15 (4) 2006, 433-446.

[19] Breeze P., Power System Energy Storage Technologies, 2018, 69-77, https://doi.org/10.1016/B978-0-12-812902-9.00008-0

[20] Czaplicka-Kolarz K., Scenariusze rozwoju technologicznego kompleksu paliwowo-energetycznego dla zapewnienia bezpieczeństwa energetycznego kraju. Część 1., http://docplayer.pl/6988267-Scenariusze-rozwoju-technologicznego-kompleksu-paliwowo-energetycznego-dla-zapewnienia-bezpieczenstwa-energetycznego-kraju.html (accessed on 10 May 2021).

[21] Tarkowski R, Wybrane aspekty podziemnego magazynowania wodoru, Przegląd Geologiczny, 65 (5) 2017.

[22] Bünger U., Michalski J., Crotogino F. & Kruck O. – Large-scale underground storage of hydrogen for the grid integration of renewable energy and other applications. [W:] Compendium of Hydrogen Energy, 2006, 133–163.

[23] ASSESSMENT of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe – HyUnder. Grant agreement no. 303417. Executive Summary 23 JUNE 2014; http://hyunder.eu/wp-content/uploads/ (accessed on 10 May 2021).

[24] https://www.ceog.fr/ (accessed on 10 May 2021).

[25] Gąsior P., Kaleta J., Wodór jako paliwo w zastosowaniach cywilnych i militarnych, Problemy techniki uzbrojenia, Wydawnictwo WITU, Zeszyt:138, Zielonka 2016.

[26] https://www.dw.com/pl/jak-słońce-zamienia-wodę-morską-w-wodór-szansa dla Portugalii/ (accessed on April 2021).

[27] https://www.gramwzielone.pl/energia-sloneczna/20532/energia-z-farmy-pv-i-magazynu-energii-za-0145-usdkwh (accessed on April 2021).

[28] Chaczykowski M., Stacjonarne ogniwa paliwowe zasilane gazem ziemnym, Nowoczesne Gazownictwo 1 (2006) XI.

[29] Rozporządzenie Ministra Gospodarki z dnia 19 grudnia 2005 r. w sprawie szczegółowego zakresu obowiązków uzyskania i przedstawienia do umorzenia świadectw pochodzenia, uiszczenia opłaty zastępczej oraz zakupu energii elektrycznej i ciepła wytworzonych w odnawialnych źródłach energii. Dz. U. Nr 261, poz. 2187.

[30] Weidner E., Ortiz Cebolla R., Davies J., Global deployment of large capacity stationary fuel cells, JRC Technical Reports, European Union, 2019.

[31] www.energy.gov - U.S. Department of Energy (accessed on April 2021).

[32] Kasirajan K., Saigeetha S., Samrot A.V., Abirami S., Renitta R.E., Dhiva S., 11 (2), 2021, 9420-9431.

[33] Geiger S., Cropper M., "Fuel Cell Market Survey: Small Stationary Applications", Fuel Cell Today, 2003

[34] http://feeds.greentechmedia.com/~r/GTM_Solar/~3/FyMLtVCQ9G8/hdf-energy-unveils-ambitious-hydrogen-project - HDF Energy Touts Big Promises for Its Hydrogen Project in French Guiana (accessed on May 2021)

[35] www.ballard.com - Ballard's Commitment to Fuel Cell Technology Innovation—for 40 Years and Counting (accessed on March 2020).

[36] www.doe.gov – (accessed on 14 May 2021).

[37] Leśniak A., Światowy rynek ogniw paliwowych, doi:10.15199/48.2020.04.41

[38] www.hydrogenandfuelcellsafety.info - Hydrogen and Fuel Cells Codes & Standards Coordinating Committee (accessed on 10 May 2021).

[39] www.fuelcelleurope.org – Fuel Cell Europe (accessed on 10 May 2021).

[40] [40] www.compositesworld.com/articles/the-markets-fuels-cells-and-batteries-The markets: Fuel cells and batteries (2021) | CompositesWorld (accessed on May 2021).

[41] [41] www.ec.europa.eu - EU funding possibilities in the energy sector | Energy (europa.eu) (accessed on May 2021).

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