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A REVIEW OF TECHNOLOGIES IN THE AREA OF PRODUCTION, STORAGE AND USE OF HYDROGEN IN THE AUTOMOTIVE INDUSTRY

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Abstract

At present, we can learn and read more and more about hydrogen in both traditional and social media. This article answers why there has been so much interest in hydrogen recently. It has been recognized by European and global decision-makers as a very promising medium necessary to carry out the climate and energy transformation. The advantages of hydrogen as a fuel and as a medium for storing large amounts of energy over a long period of time is also presented. In addition, an overview of hydrogen technologies presented at the Hydrogen Technology Expo in Bremen in September 2023 is provided. The state of hydrogen technologies currently available on the market is compared to the latest achievements of scientists as described in scientific articles. The aim of the article is to review the technologies available on the market for the production, storage and use of hydrogen as a vehicle fuel. Hydrogen technologies presented at the Hydrogen Expo in Bremen were confronted with the latest scientific achievements described in the latest scientific articles. Thanks to such a confrontation, it is possible to make a rational purchasing decision in the area of selected hydrogen technologies.

Keywords: hydrogen electrolyzer; green hydrogen; hydrogen storage; hydrogen fuel cell; fuel cell vehicle

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1. Introduction

The interest in hydrogen as a fuel in recent years is not accidental. It resulted from the enormous potential of this element as well as from the market demand. The technology of hydrogen fuel cells and hydrogen electrolysers is not new. Scientists have been working for decades on innovative materials that have special properties to split water into hydrogen and oxygen and then combine them again to obtain electricity and heat [20]. The largest quantities of hydrogen found on earth are stored in water. It is enough to recover and use in many branches of the economy, for example, as fuel for vehicles or as a substrate in the chemical industry. A very important feature of hydrogen is its zero emission in the form of carbon dioxide. Therefore, hydrogen does not contribute to global warming. But where could one get the large amounts of cheap electricity needed to produce large amounts of hydrogen? In Europe and around the world, much investment have been made in recent years in the area of energy production from Renewable Energy Sources (RES) [30]. Photovoltaic systems and wind farms are characterised by seasonality and high variability in the amount of energy produced [1]. This means that they may produce too much energy that the energy system cannot store. Sometimes, they produce very little to no energy (at night when there is no wind). Therefore, both the Polish, European and global energy distribution system needs an additional system for storing large amounts of energy, which will be charged when production from RES is high and discharged when production from RES is low. Many countries investing in renewable energy have long come to the conclusion that without services for balancing power systems, the unlimited development of renewable energy is not possible [26]. The remedy for this state of affairs turns out to be hydrogen. Although it is not easy to produce and is a highly explosive gas, it is possible to produce it in large quantities, store it and, with quite high efficiency, convert it into electricity and heat using hydrogen fuel cells [28].

Each energy transformation lasts for a specific time and requires expenditure on specific areas of scientific research, the effective commercialisation of which will allow the introduction to the market of innovative products and processes necessary for the functioning of the entire hydrogen chain. Intensive research and development has already allowed the commercialisation of many hydrogen technologies that make up the hydrogen economy, which is understood collectively as technologies for the production, storage, distribution and use of hydrogen and its derivatives, including centralised and distributed systems [58]. Economists conduct various analyses to predict the prices of green hydrogen obtained using various technologies and the costs of its storage and distribution [9, 39, 45].

The European Union countries, together with the United States of America, positively assessed the state of research and development work on hydrogen technologies and decided to introduce hydrogen into their official development strategies and it is necessary to refer to at least a few such items. *The Polish Hydrogen Strategy until 2030 with a perspective until 2040* (PSW) is a strategic document that defines the main goals of the development of the hydrogen economy in Poland and the directions of intervention that are desirable to

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achieve them. It is part of global, European and national efforts to achieve a low-emission economy. The strategic long-term goal set for the European Union (EU) is to achieve climate neutrality by 2050. The EU hydrogen strategy combines different areas of action, covering the entire value chain, as well as industrial, market and infrastructure aspects. It takes into account the perspective of technology development and innovation as well as the international dimension, planning to create conditions enabling an increase in the supply and demand of hydrogen. The EU Hydrogen Strategy also identifies 'clean hydrogen' and its value chain as one of the key areas to unlock investments to support sustainable economic growth and jobs, which will be crucial in the context of the recovery from the COVID-19 crisis.

Few Polish residents have access to confirmed information on hydrogen technologies currently offered on the European market. It was decided to check it and present it in this article. For this purpose, it was decided to participate in the Hydrogen Technology Expo Europe 2023 fair in Bremen (Germany), taking place on September 27–28th, 2023 (https://www.hydrogen-worldexpo.com/). While visiting the exhibitors' stands, one of the authors became acquainted with the current offers of the largest international companies in the field of generating, storing, transporting, refuelling and using hydrogen. He talked to the suppliers of hydrogen electrolysers and other representatives of hydrogen production technologies, purification and compression stations, stationary and mobile hydrogen tanks, and hydrogen refuelling stations for hydrogen vehicles. In the future, the knowledge and technological information obtained in this way will allow for cost-optimal and technologically optimal solutions for applications in Grupa Azoty Zakłady Azotowe Puławy S.A. (GA ZAP) in order to meet the Green Azoty Strategy. The delegation participant collected large amounts of advertising materials in the form of folders and leaflets to present them to the employees of GA ZAP. Photo and film documentation was made to visualise innovative solutions in GA ZAP and members of the Cluster – Lublin Hydrogen Valley, of which GA ZAP is the coordinator. Participation in the fair enabled the selection of components for the construction of a research station for generating green hydrogen using energy from renewable energy sources [19]. During the visit to the fair, business contacts were established with potential suppliers of hydrogen components and technologies. It was the largest hydrogen industry fair in Europe this year and participation was free of charge for visitors. According to the organisers, over 650 exhibitors engaged in the fair and were visited by over 16,500 guests. We invite you to a joint review of hydrogen technologies presented at the fair in Bremen, along with a scientific commentary that is a reference to the current state of science in this selected area.

2. Research methodology

Based on their own observations and discussions among scientists and experts in the field of research, development and implementation of hydrogen technologies, they found low public awareness in these areas. Especially new people who want to enter this area of science and business need reliable information.

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Work on this article began with desk research. In academic work, most research begins with a solid analysis of existing data: previous research, assessment of the current state of knowledge, meta-analysis of articles by other researchers. In business, such an in-depth approach is sometimes not necessary, but we recommend starting research projects with at least basic research. This allows the researcher to better understand the topic and context, and thus formulate more relevant questions and more efficiently select research methods and data sources for subsequent research. Desk research is most often used in competitive analysis. Market analysis using desk research is the fastest way to draw conclusions important for business.

The next step was to verify the information obtained in the desk research stage with the current market offer. For this purpose, one of the authors decided to participate in the previously mentioned hydrogen technology fair in Bremen. When visiting exhibitors at trade fairs, he followed a previously established information collection plan. The initial assumptions included a review of only those technologies that concern the production, storage and use of hydrogen in the automotive industry. It was planned to thoroughly familiarize ourselves with the offers of at least 30 exhibitors. This number has been reached. Research at this stage took the form of an interview. It is a research method based on direct contact between the researcher and the respondent, in the form of a conversation led by the researcher.

Preparing the interview consisted of developing a set of questions for interviewing representatives of technology companies exhibiting at the fair. Conducting the interview itself included: presenting its purpose, emphasizing the importance of the interviewee's opinion, and logically arranged clear and concise questions. The reliability of the interview was determined not by the quantity, but by the quality of the questions. During the conversations, suggestive questions were avoided, people refrained from expressing their own opinions or demanding an answer from the interlocutor, even though he clearly avoids giving it. The interviews did not last too long and were not tiring for the interviewee. Modern means of information transmission allow you to record the interview on appropriate media. For this purpose, a smartphone-type device was used. The author shot many videos and took many photos that were included in the article. The preparation of the interview results consisted in quantitative and qualitative assessment of the answers provided. When checking the results of the interview, one cannot fully trust the opinions of the interlocutors. Therefore, a critical assessment of the statements was made, guided by the criteria of sincerity and objectivity, and a confrontation with the opinions of other interlocutors was carried out.

The last step of the research was to determine the state of art. Its meaning refers to the current situation of a given technology or the most innovative art or science in particular. In the field of academic research, the state of the art refers to the construction of document analysis, which demonstrates the latest achievements in the field of hydrogen production, storage and use in hydrogenation [59]. The purpose of this analysis is a collection of sources, ideas, concepts and opinions that the researcher will confirm or reject depending on the

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result of their work. In particular, such information enables a critical understanding of the topic in order to generate new knowledge in order to develop a theoretical perspective.

The aim of the article is to review the technologies available on the market for the production, storage and use of hydrogen as a vehicle fuel. Hydrogen technologies presented at the Hydrogen Expo in Bremen were confronted with the latest scientific achievements described in the latest scientific articles. Thanks to such a confrontation, it is possible to make a rational purchasing decision in the area of selected hydrogen technologies. Many companies may decide to purchase mature technologies that have been present on the market for over a dozen years. Others will take the risk of purchasing innovative technologies that are only now entering the market. In this way, the authors want to support companies belonging to the Cluster – Lublin Hydrogen Valley in rational investment in technologies for the production, storage and use of green hydrogen in the automotive industry.

3. General characteristics of hydrogen

Upon entering the three exhibition halls of the Bremen Exhibition Center, readers are entitled to a brief description of hydrogen as a chemical element and as a fuel.

Hydrogen is a gas that forms the diatomic molecule H_2. It is colourless, odourless, non-toxic and slightly soluble in water. It is the most abundant element in the universe. On earth, it occurs mainly in chemical compounds, e.g. with water and forms organic compounds. It is the lightest element, fourteen times lighter than air and its density is 0.08375 kg/m^3 (20°C; 1 atm). A single hydrogen atom (protium isotope) consists of one proton and one electron. Hydrogen forms stable diatomic molecules that decay into single atoms at high temperatures. Hydrogen can penetrate the crystal structure of metals and dissolves in platinum, nickel, iron and copper. It causes the phenomenon of hydrogen embrittlement and the materials selected for the transport and storage of hydrogen must be resistant to this phenomenon [2].

Hydrogen has a negative Joule-Thompson effect: when the gas expands (e.g. a leak in a pipeline), the temperature of the released gas increases. It is a flammable gas. The lower explosion limit is 4.1% and the upper one is 75%. A stoichiometric mixture of hydrogen and oxygen creates the so-called fulminant mixture. Such a mixture can be obtained in the electrolysis of water.

Hydrogen is widely considered in the energy context as an energy carrier that can help reduce greenhouse gas emissions [41, 46]. High-purity hydrogen can be produced by the electrolysis of water. Hydrogen obtained in this way can be used as fuel for fuel cells. Hydrogen obtained from renewable energy sources such as photovoltaics or wind farms is called "green hydrogen" [18].

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Poland is the third largest hydrogen producer in Europe, just behind Germany and the Netherlands. The Azoty Group companies themselves currently have production capacities of approximately 450,000 tons of hydrogen per year, of which 230,000 tons of this element are produced annually in Puławy alone. Hydrogen produced by the steam reforming of natural gas is called "grey hydrogen".

Approximately 50 kWh of energy is needed to produce 1 kg of hydrogen. 1 kg of hydrogen has an energy value of 33 kWh. A volume of 27 litres is needed to collect 1 kg of hydrogen at a pressure of 700 bar. Such information is very useful for quick calculations regarding the production, storage and use of hydrogen.

4. Hydrogen production

Participation in the trade fair in Bremen confirmed that many European and global companies are developing and introducing products for the production, storage and use of hydrogen in various industries and transport. Exhibitors of various types of electrolysers used to produce hydrogen presented themselves at the fair. These were European, American and Chinese companies. The latter's participation in the fair was not very large. The latest electrolysers are offered in PEM, alkaline and the latest AEM technology (e.g. Enapter).

The latest electrolysers usually use proton [57] or ion exchange [10] membranes. The structure of the latest single electrolyser cell was presented at the fair by Nafion (see Figure 1). Nafion is a registered trademark of a material produced by the American company Du Pont and used to build both electrolysers and hydrogen fuel cells [52] and will be described in more detail in the next chapter.

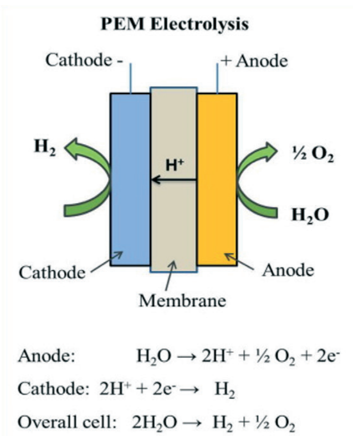

Fig. 1. Construction of a single electrolyser cell with a PEM membrane [47]

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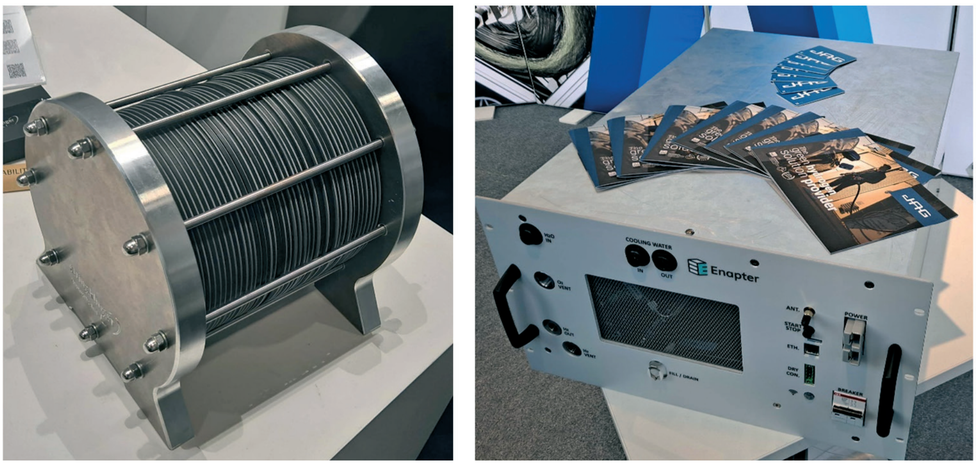
The water electrolyser consists of two bipolar plates with two electrodes between them (anode and cathode) separated by a proton exchange membrane (PEM). Bipolar plates have channels through which substrates are supplied and products of chemical reactions taking place in the electrolyser are removed [6]. Water supplies the anode side via a bipolar plate [54]. It then passes through the porous conductive layer to the anode, where, in the presence of a catalyst, it is decomposed into two protons, oxygen and two electrons [35]. The decomposition of the water molecule occurs as a result of the flow of electric current powering the electrolyser. On the cathode side, two protons that have passed through the proton-conducting membrane combine with two electrons closing the external electric circuit and create a hydrogen molecule. The PEM membrane has special properties related to the conduction of protons and the lack of penetration of water and gases such as oxygen and hydrogen.

To obtain higher yields of hydrogen produced, individual electrolyser cells are stacked. A view of the multi-cell PEM electrolyser stack itself is shown in Figure 2(a). The Figure 2(b) presents the electrolyser module which was built in a container enabling its installation in a rack cabinet. Such a module, of course, has an electrolyser stack inside, the mechanical connections of which (water supply and discharge of produced hydrogen) are placed on the front panel. There are also electrical connections to power the electrolyser and communication sockets for controlling the electrolyser and monitoring its performance and on-board diagnostics. This is possible because a set of sensors has been installed in the electrolyser module. These include pressure and temperature sensors and a flow meter that allows measurement of the amount of hydrogen produced. At the same time, the voltage and current supplying the electrolyser are measured.



(a) (b)

Fig. 2. Electrolysers: (a) multi-cell electrolyser stack, (b) electrolyser module with built-in multi-cell stack

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Exhibitors such as Linde, Siemens Energy, and ABB offered the comprehensive delivery of technological lines containing photovoltaic systems and wind energy to power hydrogen plants [32], water preparation systems, electrolysers of various power and capacity, hydrogen drying and compression systems, collection and storage technologies transmitting large amounts of hydrogen and hydrogen refuelling stations for passenger vehicles and buses. Of course, at the fair, one could meet producers of each of the above-mentioned components of such a technological line. Figure 3 shows a photo of one of the authors with a Siemens Energy electrolyser in the background. The presented facility clearly indicates that electrolysers produce hydrogen and oxygen. Recalling the basics of chemistry, it is worth repeating that to produce 1 kg of hydrogen, approximately 9 litres of water and approximately 50 kWh of electricity are needed. In the process, approximately 8 kg of pure oxygen is produced. This information is essential for those who, in addition to green hydrogen, also use oxygen in industrial processes.

Fig. 3. Siemens Energy electrolyser

At the fair in Bremen, electrolyser systems with power ranging from several kW to several dozen MW were presented. The smaller ones were built in rack cabinets (Figure 4(a)), the largest ones were intended for container construction (Figure 4(b)).

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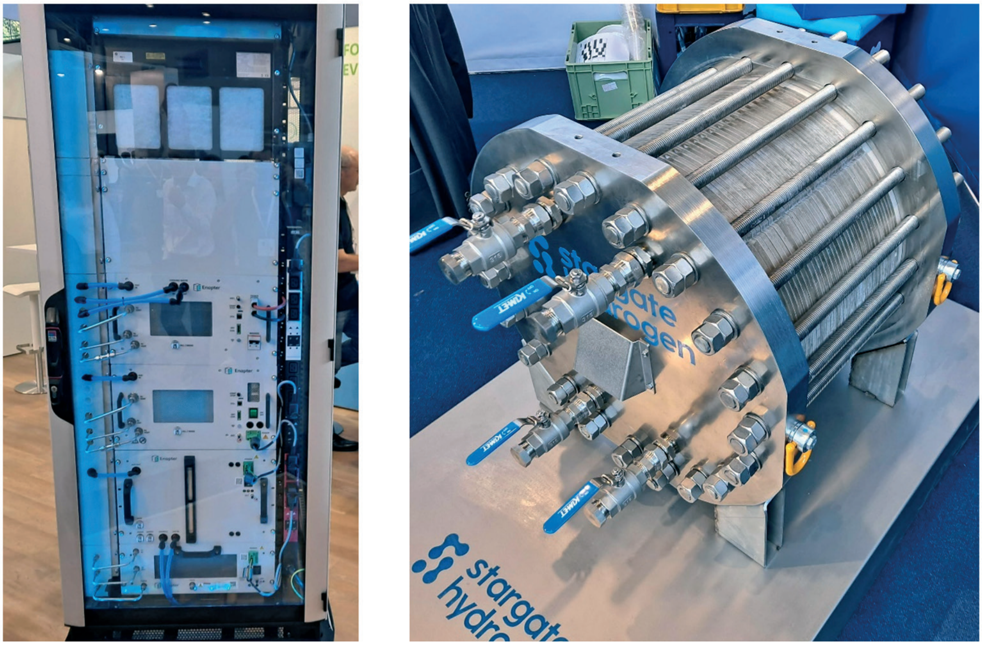

(a) (b)

Fig. 4. Electrolysers: (a) low-power AEM type by Enapter built in a rack cabinet, (b) high-power alkaline one by Stargate Hydrogen

At the fair, one could additionally meet the manufacturers of individual elements which compose the electrolysers, i.e. membranes, catalysts, bipolar plates, stack housings, seals (DuPont, Trelleborg), etc. Based on their offer, it is also possible to design and build your own hydrogen electrolyser together with suppliers of individual technologies. Exactly the same approach can be used to produce your own fuel cells. However, most of the exhibitors were integrators who are able to prepare a complete and effectively operating hydrogen production line using the design and build technology. There were also several exhibitors at the fair presenting research and educational stands in the area of green hydrogen production (Easyenergy). An important observation is that these exhibitors were eager to use Enapter electrolysers. The obvious reason for this choice is the scalability of electrolysers every 2.5 kW of power and the Internet of Things functions that enable remote viewing, monitoring and diagnostics of the entire system using computer software or applications for mobile devices. In the last days of September 2023, the Enapter presented a new line of electrolysers with power ranging from 50 kW to 120 kW.

The fair offered electrolysers in PEM [22], AEM [51], SOFC [53] and AFC [56] technologies. The latter ones are alkaline electrolysers. The offer in this regard was presented, among others, by the German company Fest. Important areas for the development of PEM

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electrolysers are increasing their efficiency [29] and preventing performance degradation [48]. Scientists are currently also developing innovative photoelectrolytic [16], photoreforming [4] and thermophotocatalytic [3] methods for hydrogen production, which may be an alternative to electrolysers.

Ultrapure water is the basic raw material for the production of high-quality hydrogen and the reliable operation of the electrolyser. Inadequate water treatment can seriously disrupt the production processes and damage the electrolyser. The selection of an appropriate treatment system depends on the selection of the electrolyser and the feed water source. The fair in Bremen featured companies providing a comprehensive solution consisting of approved equipment, the know-how and international service for the entire water preparation process from its source to the interior of the electrolyser. The Eurowater electrolysis water preparation station is shown in Figure 5.

Fig. 5. Eurowater water purification system

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5. Hydrogen fuel cells

William Grove in 1842 constructed the first fuel cell, which produced electricity by combining hydrogen and oxygen. Fuel cells are, therefore, electrochemical devices [40]. However, it took over 100 years to see its commercial application. It was not until 1956 that Harry Karl Ihrig, in cooperation with the US Air Force, used a 15 kW fuel cell in an Allis-Chalmers agricultural tractor. Fuel cells constructed in the 1950s did not find wider practical application until the United States decided to use cells with polymer membranes as a source of electricity and water in its space program. Ships such as Gemini 5 in the Apollo program and the Skylab orbital station were equipped with fuel cells. International Fuel Cells (IFC, later UTC Power) developed a 1.5 kW AFC cell for use in the Apollo space missions. The fuel cell provided electricity and drinking water for the astronauts for the duration of the mission. IFC then developed the 12 kW AFC cell, used for onboard power on all space shuttle flights. The development of a material with the trade name Nafion by Walther Grot from DuPont in 1967–69 revolutionised fuel cell technology. Nafion is a synthetic copolymer of tetrafluoroethylene and perfluorinated oligovinyl ether terminated with a strongly acidic sulfone residue.

Hydrogen fuel cells have a very similar structure to the electrolysers presented in the previous chapter. The anode side of a single electrolyser cell is powered by pure hydrogen via bipolar plates. At the anode, in the presence of a platinum (or other noble metal) catalyst, the hydrogen molecule is split into two protons and two electrons. Protons pass through the PEM proton exchange membrane and electrons flow through the external circuit to the cathode. At the cathode, two protons and two electrons react with the oxygen in the air supplying it and create water. The reaction is accompanied by the release of heat. The electromotive force of a single fuel cell is approximately 1 V or less, and the electric current in the circuit depends on the active surface area of the electrodes. The voltage can be increased by connecting many such individual cells into series. This series connection of multiple cells is called a fuel cell stack and may contain dozens or even hundreds of individual cells. The most common method of combining fuel cells into a stack is the use of the so-called bipolar plates. Their main task is to evenly distribute fuel and oxidant over the entire surface of each electrode. The appearance of the PEM fuel cell stack is shown in Figure 6(a). Other types of fuel cells can also be stacked, for example, Figure 6(b) shows a stack of SOFCs (solid oxide fuel cell). The stack in question can operate in both fuel cell and electrolyser modes. The stack consists of 119 layers that can generate 3 kW of power in fuel cell mode and 3 Nm^3/h of hydrogen in the electrolyser mode. According to the manufacturer's declaration, the stack was designed specifically for the mass production of hydrogen and has a modular structure for large-scale use. Scientists are well aware of the advantages and disadvantages of individual hydrogen technologies. It is, therefore, possible to effectively combine selected technologies depending on their application in order to obtain specific benefits. An example is the work that presents the combination of SOFC electrolysers with hydrogen fuel cells of the MCFC type (molten carbonate fuel cells) [34].

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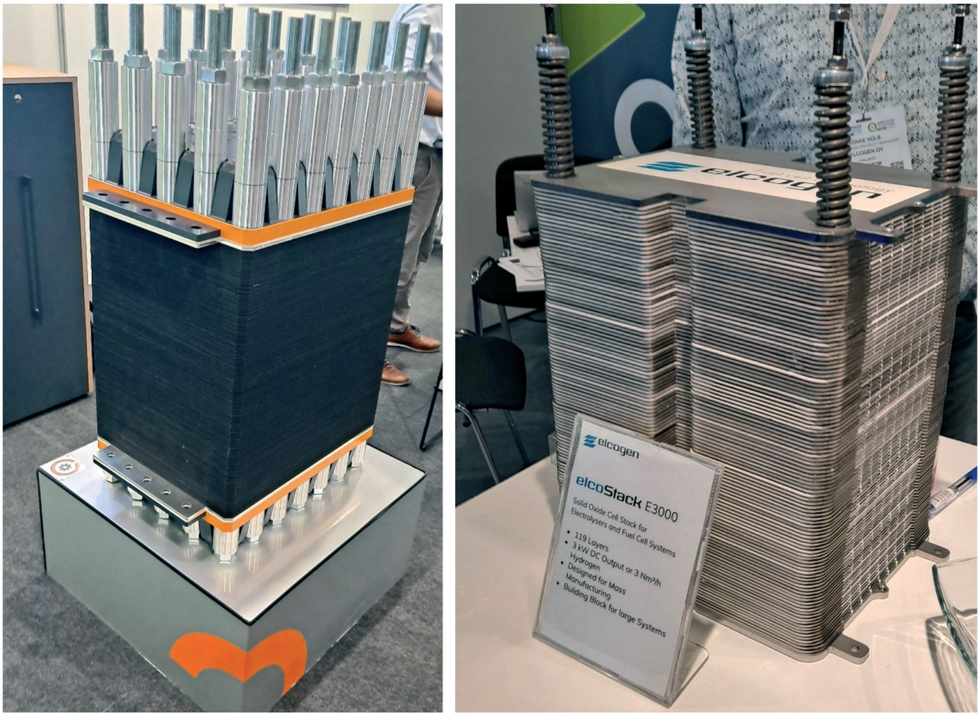

(a) (b)

Fig. 6. Fuel cell stacks: (a) PEM type by Hoeller; (b) SOFC type by elcogen

In 2018, hydrogen trains started running in Germany. Alstom Coradia iLint trains have hit the tracks in Lower Saxony, Germany. The first line operated by hydrogen-powered trains was almost 100 km long, replacing the existing fleet of diesel trains. The second decade of the twenty-first century is also the time of the market implementation of hydrogen buses. The largest companies producing buses, as part of pilot projects, develop structures, homologate and implement hydrogen buses on specific lines as part of public-private partnerships. Polish examples of such implementations are Solaris, Solbus and Ursus Bus [31].

The offer of fuel cell packages for the automotive industry was presented at the fair. Figure 7(a) shows a fuel cell package from the German company EKPO. From the specification card, we learn that it is a dual system consisting of 598 cells (2x299) with a power of 205 kW. It is a PEM system operating at low temperatures. The hydrogen fuel cell system is powered by hydrogen and air and has liquid cooling. The hydrogen pressure on the anode side is 2.7 bar and the air pressure on the cathode side is 2.5 bar. The system has an integrated water separator and a media control and monitoring system. All sensors and actuators meet automotive industry standards. The system has a shielded, electromagnetically resistant housing and meets the requirements of the IEC-62282-2 and GB/T 33978 standards. It is intended

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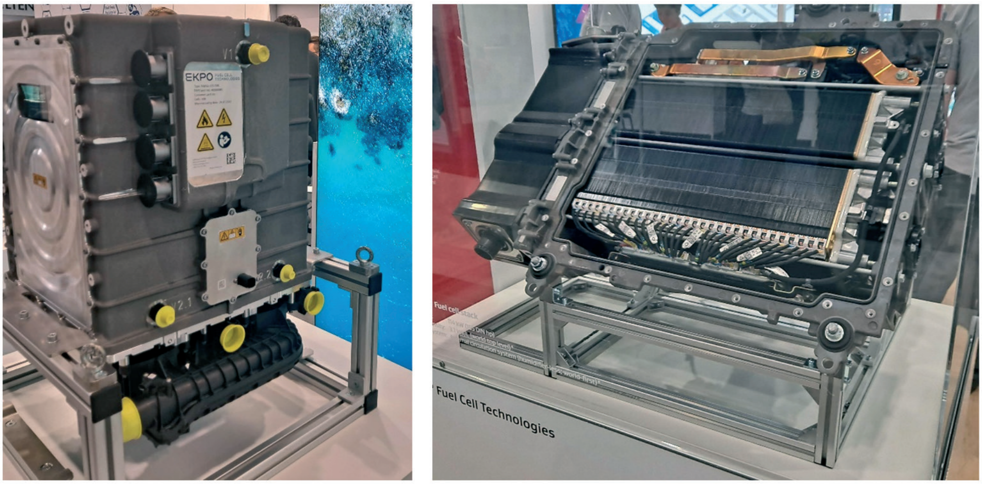
for all applications requiring power greater than 150 kW, especially for driving trucks, trains, ships [21] and even airplanes [12]. EKPO did not show the appearance of the hydrogen system inside the housing. However, this possibility was provided by GORE (Figure 7(b)). After removing the casing, two stacks of fuel cells, electrical connections and a system for monitoring the voltage of individual cells were clearly visible.



(a) (b)

Fig. 7. Fuel cell packages: (a) enclosed; (b) open

Recently, ecological hydrogen drives have also been used to power boats, yachts and small ships. Fuel cell systems for marine applications must primarily be resistant to the corrosive effects of seawater. An example of a ready-made market product in this area is the 80 kW system offered by Genevos (Figure 8). Powercellution also exhibited at the fair in Bremen with its Marine System 200, dedicated to larger vessels. It is a compact system with a net power of 200 kW, which can easily be connected in parallel to obtain a power of 1 MW. The company declares that the system was designed and developed in accordance with the rules applicable in the maritime industry.

Scientists from the University of Trieste (Italy) in cooperation with Fincantieri [5, 17] are working on the use of fuel cells to power vessels.

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Fig. 8. Fuel cell for propulsion of boats and marine vessels manufactured by Genevos

In the area of hydrogen fuel cells, scientists most often develop PEM cells operating at low temperatures of approximately 65°C. There is almost no mention of high-temperature cells of the HTPEM (high temperature protone exchange membrane) type, which have a different membrane than Nafion and operate at temperatures of 180°C to 200°C. Scientists are working on innovative designs and materials of electrodes [50], bipolar plates and catalysts [37]. Precious metals used for them are increasingly replaced by cheaper substitutes [55]. Polish scientists proposed recycling electronic scrap for the production of MCFC fuel cell cathodes [33]. An important area of the development of hydrogen fuel cells is the control of their operation. Innovative components for the construction of the entire system combined with innovative control algorithms ensure their safe and efficient operation on board current vehicles in changing operating conditions. The above overview of technologies presented at the fair in Bremen confirms that fuel cell systems dedicated to specific applications as stationary electricity and heat generators and on-board power supply systems for wheeled vehicles and floating ships are being developed and implemented.

6. Hydrogen storage

In addition to fuel cells, hydrogen vehicles also need electric motors, small lithium-ion battery packs and hydrogen tanks. There were several exhibitors at the fair offering hydrogen tanks of several generations. The latest fifth generation are metal tanks with a carbon fibre braid that can store hydrogen at a pressure of 700 bar [27]. Passenger cars are refuelled at this

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pressure. The buses are refuelled with hydrogen at a pressure of 350 bar. Tanks from the Canadian company Luxfer which are intended for use in buses are approved for twenty years and 5,000 filling cycles (Figure 9(a)). An interesting exhibition included hydrogen tanks with a cut wall (Figure 9(b)). The cut clearly shows the thickness of the metal wall and the thickness of the composite carbon-fibre braid.

(a) (b)

Fig. 9. Fifth generation composite tanks for hydrogen storage: (a) tank mounting method; (b) view of the tank with a cut wall

Based on composite technology, the American company Worthington Industries (owner of the Polish manufacturer of LPG tanks – STAKO) presented an offer of a hydrogen trailer which, when installed in a forty-foot container, is able to transport 500 kg of hydrogen at a pressure of 381 bar. This is the offer to transport large amounts of hydrogen for bus applications. This amount of hydrogen can be used to refuel twelve 12-metre buses and each of them can travel over 400 km on hydrogen [13, 14, 15]. GA ZAP is already considering the possibility of refuelling hydrogen buses with grey hydrogen and in the future with green hydrogen. A view of the Worthington Industries tank at the exhibition stand is shown in Figure 10.

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Fig. 10. Worthington Industries stand with hydrogen tanks

The production of large amounts of green hydrogen requires cheap and safe ways of transporting it [11]. Hydrogen storage systems in metal hydrides [23] or liquid organic hydrogen carriers (LOHC) [43] are also very promising, and are one of the best options for transporting hydrogen over long distances [24]. A feature of both of these systems is the ability to absorb hydrogen at ambient temperature and release it after slight heating [38]. Currently, there are metal hydride hydrogen storage systems on the market that can store significant amounts of hydrogen. Scientists are considering the economic aspects of their large-scale use [7]. The system presented in Figure 11 is capable of containing 10 kg of hydrogen in a small volume (approx. 1 m^3).

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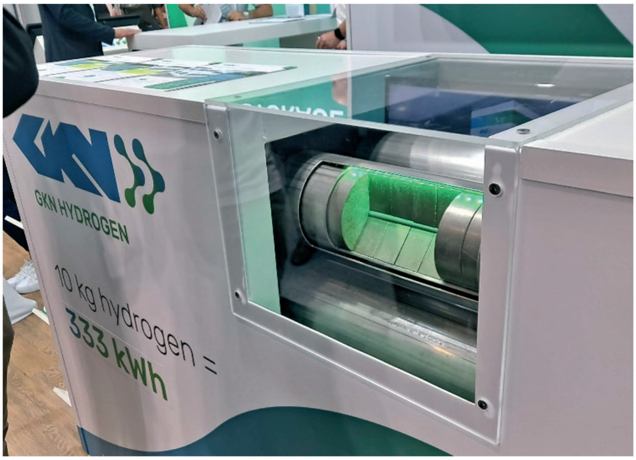

Fig. 11. Hydrogen storage system in metal hydrides by GKN Hydrogen

Hydrogen can be stored and transported in liquid form to save space [49]. Liquid hydrogen (LH_2) has been used since the 1960s as a liquid fuel for space applications. Recently, new manufacturing processes and new environmental regulations have increased interest in the use of hydrogen, with the most popular application being in fuel cells for land and marine vehicles. Presented at the Bremen fair, Cryostar has developed a range of cryogenic pumps specially designed to transfer and compress liquid hydrogen at a temperature of –253°C.

7. Vehicles powered by hydrogen fuel cells

An important thematic and product area of the fair were vehicles powered by hydrogen fuel cells. Several Toyota Mirai vehicles could already be seen in the parking lot in front of the exhibition halls. There was also such a car at one of the stands (Figure 12(a)) and visitors could look under the bonnet of such a hydrogen vehicle (Figure 12(b)). Toyota is one of the leaders in the automotive industry that has commercialised hydrogen-powered passenger vehicles. In the case of the Toyota Mirai, the fuel cells are placed under the hood of the car, and the hydrogen is located in three tanks that can hold a total of up to 5.6 kg of this gas. Refuelling a hydrogen car is not only very simple, but also extremely fast and safe. In the case of the Toyota Mirai, it takes less than 5 minutes to completely fill the tanks with hydrogen with a total capacity of 142.2 litres. A Toyota Mirai hydrogen car consumes on average 0.84 kg of hydrogen per 100 km. With tanks holding a total of 5.6 kg of this gas, this gives a range of up to 650 km on one refuelling. The fuel cell set used in this model generates a maximum power of 182 HP, which is 10% better than the previous generation of the car. Due to this, the hydrogen-powered Toyota Mirai accelerates from 0 km/h to 100 km/h in nine seconds, and from 40 km/h to 70 km/h in 2.8 seconds. The maximum speed of the vehicle is 175 km/h.

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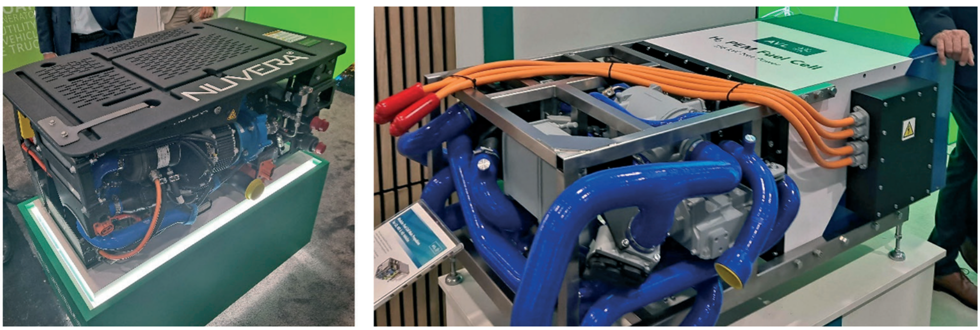
(a) (b)

Fig. 12. Toyota Mirai powered by hydrogen: (a) view of the vehicle; (b) drive system

The stands of manufacturers of fuel cell stacks and all the accessories were also visited. They constitute an on-board system for converting the chemical energy contained in hydrogen into electricity and heat. Figure 13(a) shows the fuel cell system offered by the American company Nuvera, and Figure 13(b) by AVL. It is an Austrian company from Graz, engaged in research, development and implementation of ecological vehicle power systems and exhaust gas analysers. As we can see in the drawings, these are complete mechatronic systems for generating power in the form of electricity and heat on board vehicles. They also contain their own control systems which are researched and developed by scientists in order to optimise performance, increase operational reliability and extend the time of correct operation [8, 36]. Research experience at the PhD level of one of the authors shows that controlling the air flow in fuel cell systems is very important and affects the performance and correct operation of the entire system. Hydrogen drives of vehicles are characterized by high efficiency of converting the chemical energy of hydrogen into energy driving the wheels [25], which reduces the total costs of using such vehicles [44].



(a) (b)

Fig. 13. Fuel cell system: (a) by Nuvera; (b) by AVL

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Many automotive companies conduct intensive research or have implemented hydrogen vehicles on the market. At the fair in Bremen, opposite the producers of fuel cells for automotive applications, there was an offer from a French company offering tests and approvals of hydrogen vehicles. The final test that concludes experimental development work on hydrogen components in vehicles before their market implementation is homologation testing. First of all, they confirm the safety of approved components [13]. Hydrogen vehicles must also have comprehensive approval.

The information obtained at the exhibition stand shows that the French company Emitech offers a wide range of tests of hydrogen components and vehicles. We can find out that hydrogen tanks and multi-valves are tested in accordance with the requirements of UNECE Regulation 134 and ISO/TR 15916 and SAE J2579 standards. These tests include hydraulic and pneumatic testing as well as fire testing. The research offer for fuel cells themselves usually concerns compliance with the requirements of vehicle manufacturers in relation to the supplied OEM components. These include mechanical, electrical and EMC tests carried out in a Faraday cage and climatic chambers. The traction batteries of hydrogen vehicles, like the batteries of electric vehicles, are tested in accordance with UN ECE Regulations 10, 100 and others. Electric traction motors must meet the requirements set out in UN/ECE Regulations 10, 85 and 101. In September 2023, the company opened a new test center in France specifically for hydrogen fuel cell vehicles (Figure 14).

Fig. 14. Opening of a new testing center for hydrogen fuel cell vehicles in Bourgoin-Jallieu (France) [42]

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Figure 15 shows a Mercedes truck with a GVW of 16 t powered by hydrogen fuel cells. As you may notice, it was very popular with the visitors. According to the manufacturer's data, the vehicle's tanks can hold a maximum of 32 kg of hydrogen compressed to 700 bar, which gives the vehicle a range of approximately 500 km. The directions of work in this area include the use of hydrogen propulsion to power trucks used especially in urban traffic conditions. Hydrogen drives, like battery electric drives, are quiet and do not emit any harmful pollutants into the atmosphere at their place of use. For this reason, they are eagerly used by municipal cleaning companies and logistics operators dealing with the distribution of general cargo.

Fig. 15. A hydrogen-powered truck

8. Hydrogen compression and refuelling

To achieve a sufficiently long range on one refuelling, hydrogen vehicles need large amounts of hydrogen stored on board. The most commonly used method of storing hydrogen in practice is its compression to a pressure of 350 bar (standard for buses) and up to 700 bar (standard for passenger vehicles). Among the many suppliers of hydrogen compression technology, the companies that stood out were Maximizator (Figure 16(a)) and Hiperbaric (Figure 16(b)). The latter offers the possibility of compressing hydrogen up to 1000 bar. Hydrogen produced in the electrolyser has a pressure ranging from several to several dozen bars and must usually be compressed to 350 bar or 700 bar.

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(a) (b)

Fig. 16. Hydrogen compressor: (a) from Maximator; (b) from Hiperbaric

Hydrogen dispensers are used to fill hydrogen vehicles with hydrogen fuel (Figure 17(a)). They look like the well-known dispensers of liquid or gaseous fuels such as LPG or CNG. They differ from the latter in the level of gas pressure and the type of hydrogen refuelling nozzle. Weh offered a wide selection of hydrogen refuelling valves at the fair (Figure 17(b)). Hydrogen dispensers were also offered by the American company Dover Fueling Solutions. Therefore, due to highly developed and approved technologies, refuelling hydrogen vehicles is very fast and safe.

(a) (b)

Fig. 17. Hydrogen refuelling technologies: (a) Gilbarco Veeder-Root hydrogen dispenser; (b) Weh hydrogen refuelling nozzles

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9. Conclusions

Large financial outlays incurred after 2000 by some European countries and around the world have brought tangible benefits in the form of new products and services in the area of hydrogen production and use in the automotive industry.

In the field of hydrogen production, the dominant technology is the use of various types of water electrolysers. Alkaline electrolysers are still the most frequently used on the market, followed by PEM membrane electrolysers and AEM electrolysers, which are rapidly gaining popularity. They are characterised by a number of beneficial properties compared to their predecessors, but more on this will be discussed in the subsequent scientific articles. It is also worth mentioning SOFC electrolysers which can be powered by waste steam instead of water and are then characterised by greater operational efficiency. Different types of electrolyzers have their advantages but also disadvantages. Some operate at low temperatures and are powered by liquid water, while others operate at high temperatures and may be powered by waste steam. Therefore, the choice of the appropriate electrolyzer depends on its application. Designers developing hydrogen production systems using Renewable Energy Sources should have extensive knowledge of electrolysers available on the market. The appropriate selection of the electrolyzer will affect the reliability of its operation as well as the price of the produced hydrogen.

In the area of hydrogen fuel cells, scientists most often develop PEM cells operating at low temperatures of approximately 65°C. There is almost no mention of high-temperature HTPEM cells, which operate at temperatures of 180°C to 200°C. Scientists are working on innovative designs and materials of electrodes, bipolar plates and catalysts. Precious metals used for them are increasingly replaced by cheaper substitutes. The offer presented at the fair in Bremen confirms that fuel-cell systems that are being developed and implemented are dedicated to specific applications such as stationary electricity and heat generators and also as on-board power supply systems for wheeled vehicles, floating ships and even airplanes.

In the field of hydrogen storage, compression to high pressures of 350 bar for buses and 700 bar for passenger cars dominates. Currently, enough hydrogen can be stored in high-pressure composite tanks to cover a distance of approximately 500 km. Compression is performed using multi-stage mechanical compression systems and the offer in this area is rather extensive. There is also no problem in choosing the systems for transporting compressed hydrogen over long distances from many possible offers. There was also a wide range of hydrogen distributors for vehicles and entire hydrogen refuelling stations.

The most common type of vehicles powered by hydrogen fuel cells is the city bus (even though the market offer presented at the fair in Bremen also included passenger cars where Toyota is leading in this regard with its Mirai model). Trucks and vessels can also be powered by hydrogen fuel cells.

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Among the offers presented at the Hydrogen Technology Expo by over 650 exhibitors, one can easily choose the components to build the green hydrogen production line or to power any vehicle using hydrogen fuel cells. The authors intend to continue their own research in the area of hydrogen technologies and closely monitor their development in Europe and around the world. This technology may be used in the production of green hydrogen by GA ZAP and members of the Cluster – Lublin Hydrogen Valley, of which GA ZAP is the coordinator.

The approach used to review hydrogen technologies has certain limitations. The article was written based on a visit to one international fair. There were representatives of companies from Europe, the United States of America, Asia and many other countries. However, there were no representatives of Australian companies that are very advanced in hydrogen technologies. A visit to similar trade fairs held in Asia could contribute to including more technologies and companies from more countries in the review article.

10. Acknowledgement

The paper submitted for the first time for publication in our periodical will be treated as an original. After the peer reviews are received, all changes to the paper should only be made in the "Track changes" mode.

11. Nomenclature

GA ZAP	Grupa Azoty Zakłady Azotowe Puławy S.A.
RES	Renewable Energy Source
PEM	Proton Exchange Membrane
AEM	Aion Exchange Membrane
AFC	Alkaline Fuel Cell
SOFC	Solid Oxide Fuel Cell
MCFC	Molten Carbonate Fuel Cell
FCV	Fuel Cell Vehicle

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