OVERVIEW OF THE CURRENT STATE OF HYDROGEN MANAGEMENTAND ITS TECHNOLOGIES IN POLAND

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Introduction

Climate change caused by greenhouse gas emissions is forcing humanity to accelerate decarbonization processes in the global economy in virtually all areas. One of these processes is an energy transition aimed at replacing fossil energy sources with renewable ones that provide so-called green energy. This can come from harnessing the power of wind, water, solar, biomass and green hydrogen (Łącka, 2023). The European Union was the first economic grouping to make the fastest decision to start implementing the recommendations enshrined in the UN resolution Agenda 2030 (UN, 2015). The European Commission in 2019, as part of its climate protection policy, announced the tenets of the European Green Deal (EC, 2019). Since then, decarbonization in EU member states has accelerated rapidly. Within the framework of the Green Deal strategy, a number of important decisions and actions have been taken in the following years, first to achieve a 55% reduction in CO emissions in the EU by 2030_2 , and ultimately to ensure the Community's climate neutrality by 2050. Among these actions were the adoption of an EU hydrogen strategy in 2020. (EC, 2020), as well as the submission of legislative proposals contained in *Fit for 55* in 2021. (EC, 2021). It contains provisions to bring EU law in line with ambitious climate protection policies. They require regulatory, organizational and technological changes in all member countries, not only in the energy sector, but also in other areas of the economy, including industry, transport, heating, construction or agriculture.

All countries that have signed the *Fit for 55* legislative package are aware that in order to achieve the EU's ambitious climate goals, it is necessary to develop alternative forms of energy generation and storage. One of the solutions turns out to be hydrogen, which can serve to decarbonize, among other things, the metallurgical and chemical industries, where CO_2 reduction with currently available methods is difficult for technical reasons.

Russia's attack on Ukraine in February 2022 and the global energy crisis have made everyone in Europe realize that the dependence of their economies on fossil fuels (oil and gas) threatens not only the climate, but also national security. The changed geopolitical and, consequently, economic situation revealed the need to accelerate energy transition

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processes in EU member states using new green energy solutions, including those based on hydrogen technologies (Łącka, Wojdyła, 2022). As M. Sobolewski points out, hydrogen "can replace fossil fuels in transportation and industry, as well as be used to store electricity obtained from renewable sources" (Sobolewski 2022). Widespread use of hydrogen in Europe would reduce imports of fossil fuels (oil and natural gas, coal and lignite), thereby improving energy security by stabilizing the energy system. This is particularly important for countries that have hitherto been highly dependent on oil, natural gas and coal imports from Russia. Although they have changed the structure of supply of energy carriers after the start of the war between Russia and Ukraine, their energy mix still shows a strong dependence on hydrocarbons and too small a share of renewable energy sources in total energy consumption. Poland is such a country, hence the need for an energy transition in the country. On the one hand, this is dictated by the need to decarbonize the economy in line with the European Green Deal and the *Fit for 55* document, and on the other hand, it stems from the natural need for energy and national security in terms of access to energy in a situation where its consumption is steadily increasing in line with economic growth and development, and the previous long-standing supplier (Russia) has become a threat.

A chance for Poland to free itself from the use of fossil fuels is, in addition to the renewable energy sources from conventional sources (solar, wind, water, biogas) already known and developed in our country for some time, hydrogen obtained in an environmentally friendly way. As the authors of the report *Green Hydrogen from Renewable Energy Sources in Poland* point out, "However, in order for hydrogen to fulfill its role in the decarbonization of European economies, it is necessary to ensure access to emission-free technologies for its production. In Polish conditions, the key role in the production of clean hydrogen should be played primarily by renewable sources, whose work, thanks to the properties of hydrogen that allow energy storage, will stabilize the National Electricity System in an even better way" (Brodacki et al., 2021, p. 25).

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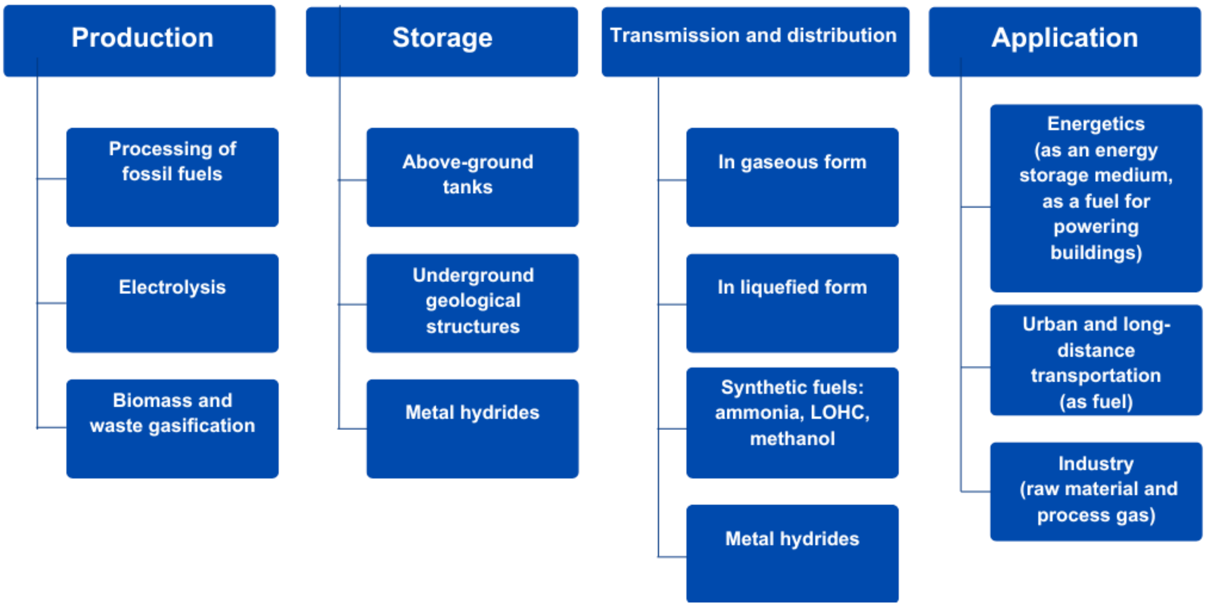
The value chain of the hydrogen economy in Poland

The complexity of the hydrogen technology field and the hydrogen economy itself, on the one hand, requires that it be properly defined using the hydrogen economy value chain concept. It can be used when describing the processes, technologies and challenges

related to the creation and development of this industry in the Polish economy. Using the definition cited by the experts of the Polish Industrial Development Agency, we can explain that "the hydrogen economy is a value chain related to the production, transmission, storage and application of hydrogen in all areas of human activity, in particular in the main sectors of the economy - transport, energy, heating, and above all in industry" (PARP, 2022, p. 12). Such an approach to the hydrogen economy, together with an analysis of the technologies necessary for the realization of the various stages of the value flow, along with a snapshot of the market position of the various links in the value chain, makes it possible to identify and assess Poland's hydrogen potential. It corresponds to the approach used by a team of experts led by G. Tchorek, who prepared a comprehensive report entitled *Value Chain of the Hydrogen Economy in Poland* (Tchorek et al. 2023a). Figure 1 shows an example of the hydrogen economy value chain, which can be used for further analysis in this area.

Figure 1: Hydrogen economy value chain



Source: own compilation based on: PARP (2022); Sobolewski (2022).

As G. Tchorek stated, the European Union has very precisely defined the conditions for the production and characteristics of hydrogen that can be considered low-carbon, and thus determined which hydrogen projects can receive funding. They point out that only hydrogen production based on electrolysis using energy obtained from RES (wind, solar or nuclear) meets the EU taxonomy, i.e. involves emissions of 3 t CO_2 per 1 t H_2 . "Steam reforming of methane (+CCS), steam reforming of biogas and waste processing (+CCS) would require additional reductions at the storage and transport stages to meet this limit. The other methods: coal gasification (+CCS), steam reforming of methane, waste processing, coal gasification and electrolysis with grid energy would not be considered low-carbon by the Union" (Tchorek et al., 2023a).

Polish Hydrogen Strategy as a determinant of the development of the hydrogen economy in Poland

Poland has joined the development of the hydrogen economy in Europe by adopting a hydrogen strategy in 2021 entitled *Polish Hydrogen Strategy to 2030 with an Outlook to 2040* (Monitor Polski, 2021). This is the most important strategic document referring to the assumptions of the European hydrogen strategy, as well as global, EU and national efforts to create a low-carbon economy. This strategy (referred to as PSW for short) sets out the main goals for the development of the hydrogen economy in Poland, as well as the directions of state intervention that are necessary to achieve these goals. It includes an expanded (compared to the one presented in Figure 1) form of the hydrogen economy value chain. It represents a blueprint for a more complex hydrogen economy value chain, which takes into account in four links of the chain new technologies, not yet operating in the Polish economy, that may develop in the coming years and create opportunities for value extraction. Table 1 shows this new forward-looking vision of the value chain of a developed hydrogen economy in Poland. Each of the components of the hydrogen economy value chain included in Figure 1 and Table 1 involves the use of different technologies, which are characterized by different measures of CO_2 , the amount of the average cost of producing 1 kg of hydrogen (H_2) and the degree of technological readiness (TRL).

Table 1. Proposed future value chain of the hydrogen economy in Poland

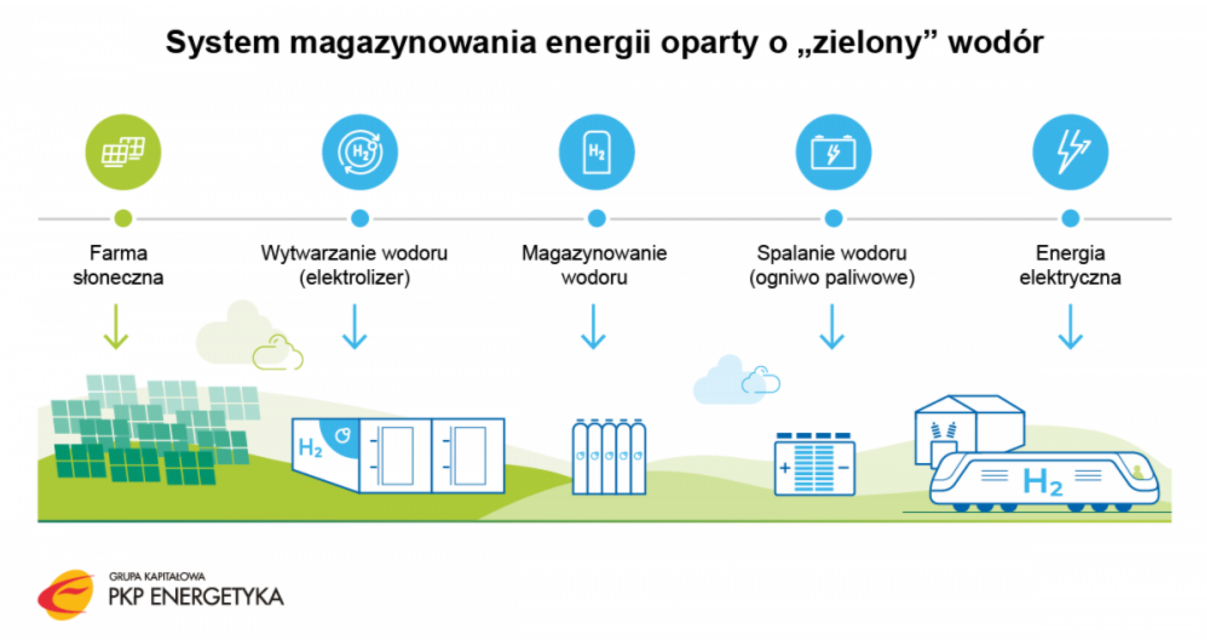
	Cells of the hydrogen economy value chain			
Hydrogen technologies and their applications	**Production**	**Storage**	**Transmission and distribution**	**Application**
	Electrolysis	Underground storage - depleted oil and gas fields, salt caverns	Transmission by means of gas networks	Stabilization of RES and national power grids
	Steam reforming of biomethane	Above ground storage - pressure vessels	Maritime transport	Energy-intensive industries (heavy, chemical, refining, fertilizer)
	Gasification, fermentation or pyrolysis of biomass	Chemical storage	Transportation of gaseous and liquefied hydrogen by tanker trucks	Fuel in cogeneration and polygeneration systems

	Steam reforming of biogas	Liquid hydrogen storage	Hydrogen refueling and bunkering stations	Fuel in road (urban and long-distance), rail, water, air and intermodal transport modes
	Gasification, pyrolysis and thermal treatment of waste	Injection of hydrogen into the gas network		Energy storage
	Steam reforming of hydrocarbons with CCS/CCU			Support for merging economic sectors
	Coal gasification with CCS/CCU			
	By-product of refining processes			
	Coke oven gas separation			
	HTR			

Source: own compilation based on: Monitor Polski (2021).

The creators of the Polish Hydrogen Strategy assumed that in Poland the hydrogen economy would be developed based on the Power-to-X model. Its concept is based on increasing the use of renewable energy to produce hydrogen, and then using it in further sectors of the economy to decarbonize them. An example of how to use "green" hydrogen in rail transportation is shown in Figure 2.

Figure 2: From producing low-carbon hydrogen to powering a train



Source: Elisabeth (2023).

The following specific goals are written in the strategy document for the hydrogen economy in Poland:

- Implementing hydrogen technologies in the power, heating and transportation industries,
- Support for decarbonization of industry, and highly energy-intensive sectors of the economy where electrification is too costly or impossible,
- Hydrogen production in new installations,
- efficient safe industry, distribution and storage of hydrogen,
- opportunities to retrain the workforce from sectors at risk of reduction, such as coal and lignite mining, for the development of the hydrogen economy,
- Creating a stable regulatory environment.

The hydrogen strategy has adopted very ambitious plans to achieve the indicated goals, including, among others (Monitor Polski, 2021):

- Achieving up to 50 MW by 2025. , and 2 GW by 20230 of low-carbon hydrogen plant capacity,
- using 100-250 by 2025 and 800-1000 hydrogen buses in urban transportation,
- Organizing at least 5 hydrogen valleys,

- Creating at least 32 hydrogen refueling stations by 2025.

The PSW was approved and adopted for implementation during the rule of the United Right, which planned to allocate about PLN 11 billion for the purposes listed above (Pilszyk et al., 2023). Potential sources of funding for these investments were to include the National Fund for Environmental Protection and Water Management (NFOŚiGW). For funding research work related to hydrogen technologies, the National Center for Research and Development (NCBiR). In addition to national sources, the strategy indicated the need to use EU funds, including the National Plan, the Horizon Europe program, *Important Project from Common European Interest (*IPCEI) competitions of the Reconstruction Fund (Next Generation EU) or the *Just Transition Mechanism.*

The government at the time planned to allocate funds from various public and private sources, including funds from the National Reconstruction Plan (NRP), to implement the PSW's intentions. From this source, €800 million was to be used to provide grants to the private sector for projects related to the use of hydrogen as a fuel in transportation and industry. The United Right government's long-running conflict with the European Commission over the rule of law has made it impossible to obtain EU funds from the NIP and thus allocate some of them for the development of the hydrogen economy.

The indicated level of necessary investment to achieve the goals of the PSW was underestimated from the beginning. Experts indicated that 2 billion PLN should have been invested in the development of the hydrogen economy in Poland by 2025, and about 17 billion PLN by 2030. Due to the changed geopolitical and economic conditions since 2022 (war in Ukraine), the level of public support and private sector investment in such long-term and risky hydrogen projects assumed by the state could not be met in the following years (Kryczka, 2021; Mierwiński, 2022; Łącka, Wojdyła, 2022).

In addition to the problems of financing the development of the hydrogen economy, regulatory difficulties arose from the outset in the implementation of the PSW. In preparation for a stable regulatory environment for the development of the hydrogen economy in Poland, the strategy established that (Wyszkowski et al., 2022):

- A regulatory framework for the operation of hydrogen as an alternative fuel in transportation will be established in Q3 2021,
- The legislative development of the hydrogen package will take place in Q4 2021.

The regulatory package, commonly known as the Hydrogen Law, was to include amendments to such laws as the Energy Law, the Law on Electromobility and Alternative Fuels, the Law on Renewable Energy Sources and the Law on Bio-Components and Liquid Biofuels. On top of this, it was intended to introduce, among other things, a legal framework that takes into account cross-sectoral opportunities for hydrogen application, systemic support mechanisms for conducting research and development activities for hydrogen technology projects, establish a national hydrogen network operator, define regulations on the environmental impact and use of hydrogen investments, and amend the construction law on hydrogen stations, taking into account facilities for their purification (Wyszkowski et al., 2022).

Unfortunately, in spite of the legislative timetable adopted, there have been delays in the introduction of hydrogen technology regulation and support in Poland from the beginning. They hindered, on the one hand, the acceleration of the development of hydrogen technologies, and, on the other hand, the raising of funds for research and development in this field, as well as the development of technologies and their commercialization. As early as 2022, representatives of the private sector pointed to the existence of negligence in the regulatory measures necessary for the development of the hydrogen economy in Poland. They stressed the need to create appropriate definitions of hydrogen, to simplify and shorten the administrative procedures necessary when making hydrogen investments. Entrepreneurs expected that such investments located in hydrogen valleys could count on greater care from the public administration.

Among the barriers perceived since the government's adoption of the PSW, private sector representatives also pointed to the unstable regulatory environment and excessive

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bureaucracy, the lack of systemic solutions (including training of officials in issuing environmental decisions on hydrogen technologies) and the discretionary nature of official decisions, the lack of precise regulations when planning, implementing or operating hydrogen investments. This made it difficult for entrepreneurs to estimate the time and cost needed to implement the project. Problems with connecting RES devices to the power grid, the lack of a coherent certification system for renewable hydrogen, the lack of rules for human safety and environmental protection in connection with the use of hydrogen, and the lack of a description of the hydrogen economy from the technical side were also considered as destimulants for the development of the hydrogen economy in Poland (Wyszkowski et al., 2023).

However, as of 2023, according to the authors of the report *The Value Chain of the* Hydrogen *Economy in Poland,* "the Polish regulatory environment for hydrogen and derivatives is gradually beginning to develop in response to very strong regulatory dynamics at the European level" (Tchorek et al., 2023a, p. 24).

The outbreak of war in Ukraine, the sharp increase in gas prices, the energy crisis in the European Union, the adoption of the REPowerEU plan, the increase in EU climate targets and technological developments, have made it necessary to revise the provisions of the PSW. At a February 2024 meeting, the new chairman of the Coordinating Council for the Hydrogen Economy pointed out "the need to revise the Polish Hydrogen Strategy to 2030, with an outlook to 2040 (PSW), due to dynamically changing energy and climate needs, including EU requirements obliging greater use of renewable hydrogen. He stressed that the development of the hydrogen economy is no longer just an alternative, but a necessity, and renewable hydrogen will find application in many sectors, including energy, industry, transportation and heating" (8th meeting of the Coordinating Council for Hydrogen Management , 06.02.2024).

According to experts (Smoleń et al., 2023), the Polish Hydrogen Strategy focuses on the development of the domestic hydrogen market and basically does not take into account aspects related to the global hydrogen market and the international competitiveness of

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hydrogen production in Poland. Given the very undeveloped Polish market for low-carbon hydrogen, one should consider the need to import this type of energy resource in the initial stages of the development of the hydrogen economy in Poland, while maintaining an appropriate level of supply diversification. One of the goals of the EU's strategic plan prepared in response to Russia's assault on Ukraine, titled *REPower EU* published in 2022 (EC, 2022), is to diversify energy supplies with the assumption of moving to clean energy as soon as possible. It points to the need to import gas and hydrogen within the EU and from third countries (Energy Community contractors), for which the established secure online purchasing platform for LNG and hydrogen imports (EU Energy Platform) is to be used. If the global market for low-carbon hydrogen (or ammonia) really develops, Poland may be inclined to import green hydrogen for economic reasons. As Smoleń and his team point out, it is necessary to establish regional energy cooperation to stabilize and secure the energy system. Depending on the direction of technology development, this could mean developing cross-border hydrogen pipelines that would allow Poland to transport hydrogen in both directions (import and export).

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Hydrogen management in Poland - current status

Hydrogen production in the value chain

In 2024, Poland, compared to other European Union countries, is at the initial stage of implementation and development of the hydrogen economy, and has failed to achieve the PSW goals intended by 2025. In the third decade of the 21st century. Poland is the third, after Germany and the Netherlands, producer of "gray" hydrogen in Europe in the manufacturing processes of the petrochemical and chemical industries, which comes primarily from the steam reforming process of hydrocarbons. It is produced at industrial plants, where it is also used for the chemical, refining, food and metallurgical industries. In 2022. Poland produced 1.3 million tons of hydrogen, with it generated exclusively from fossil fuels (Sobolewski, 2022; Pilszczyk et al. 2023). This represented more than 13% of the EU's annual production of the resource. In Poland, there are planned investments in the hydrogen economy, which assume the production of "green" hydrogen from RES (only pilot projects are currently in operation), but to a large extent investment activities are also to focus on the production of "blue" hydrogen (obtained using CO capture and storage methods$_2$). On the one hand, the indicated activities can take advantage of the opportunity arising from the high domestic demand for low-carbon ("green") hydrogen. Poland represents a promising market for hydrogen because of its significant potential demand due to its large population, dependence on fossil fuels for power and heating and transportation, and developed industry. On the other hand, current hydrogen technologies leading to the production of "gray" hydrogen are a burden on the economy (Antas et al. 2021) due to the carbon intensity of this type of hydrogen. "Gray" hydrogen will have to be gradually replaced by renewable and low-carbon hydrogen.

Data from the European Hydrogen Observer in Poland shows that in 2022, domestic demand for hydrogen was more than 784,000 tons per year. More than 96% of it was consumed in oil refining and ammonia production. Demand for hydrogen for the production of other chemicals was 14 thousand tons per year. In contrast, consumption of hydrogen for the production of industrial heat and for other purposes accounted for 9 thousand and 6 thousand tons per year, respectively. The transportation (mobility) sector used only 13.8 t (about 0.014 thousand t) of hydrogen per year (Pilszyk et al. 2023).

Experts from the Polish Economic Institute reported that in 2023 there were 74 entities related to hydrogen investments. They were characterized by different sizes, forms of ownership and belonging to different sectors of the economy (PIE, 2023). They included small entities with hydrogen refueling stations, research institutes and the largest players in the Polish fuel and energy market. The most numerous were those operating in industry and heating (24), manufacturing (14) and education (14). Entities involved in the development of the hydrogen economy in Poland include automotive corporations, energy companies, ports, gas companies, coal companies, business environment organizations (e.g. clusters, technology parks, chambers of industry and commerce), universities, research institutes and public administration institutions. Their activities are concentrated in the hydrogen valleys that have been created over the past few years. According to information from the Industrial Development Agency S.A., there are eleven hydrogen valley projects in operation in 2024. Eight of them were consulted or created on the initiative of this company, which is actively involved in the development of the hydrogen economy ecosystem in Poland. The idea behind hydrogen valleys is to support the decarbonization of energy-intensive industry, locate technology demonstrators in industrial parks and special economic zones, and build the Polish supply chain with the support of business, science and local administration (IDA S.A., 2024). Figure 3 shows the location of hydrogen valleys in Poland.

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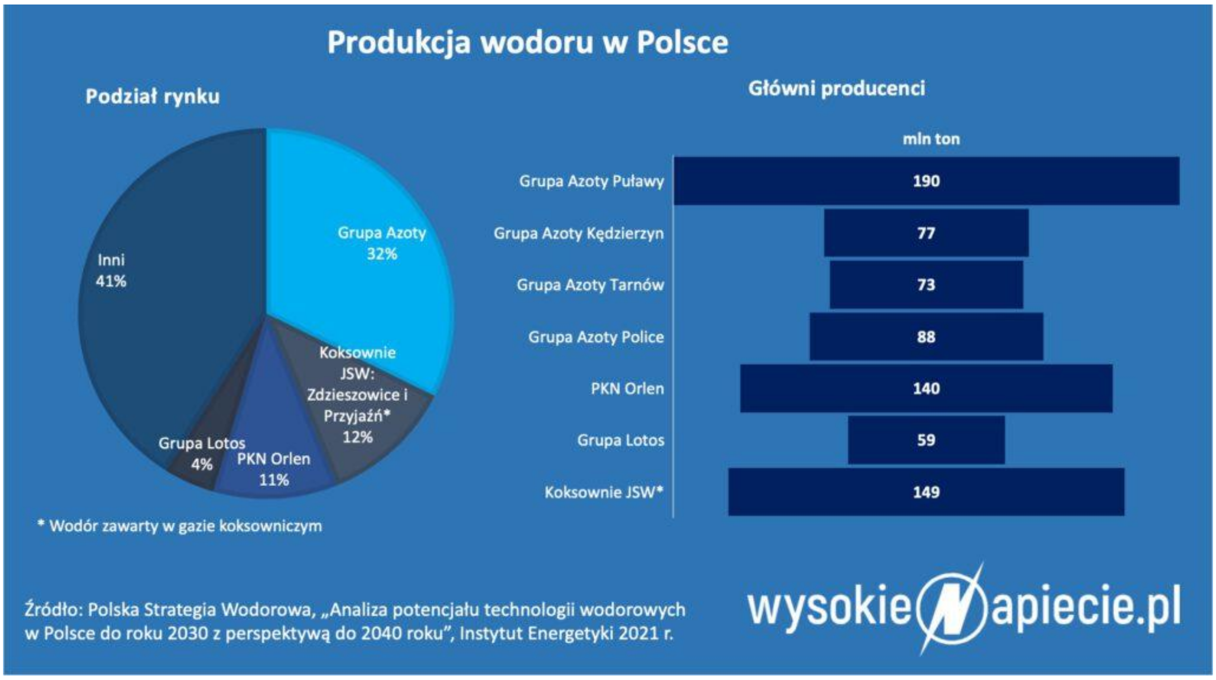
Figure 3: Hydrogen valleys in Poland in 2024.

Source: IDA. S.A. (2024).

The largest producer of hydrogen in Poland is Grupa Azoty S.A. (producing mineral fertilizers and chemicals). Significant amounts of conventional hydrogen (from natural gas) are also produced at PKN Orlen, the Przyjazn coking plant, which belongs to Jastrzębska Spółka Węglowa. This shows that hydrogen in Poland is produced by large state-owned companies and consumed primarily for their own needs without much opportunity for resale. As Komorowska et al. point out. (2023) it is difficult to talk about the hydrogen market in Poland today - it has yet to develop. Figure 4 shows the hydrogen production volumes of individual producers in Poland in 2021. Note that in 2022 there was a merger between PKN Orlen and Grupa Lotos, so now only PKN Orlen is on the market as a hydrogen supplier from the fuel and refining sector.

Figure 4 Hydrogen producers in Poland and their market shares



Source: Elizabeth T. (2023).

Hydrogen produced in Poland is mainly used in the chemical industry to produce ammonia, used in the production of fertilizers. In addition, it is used in the petrochemical industry in the processes of reforming (used to improve fuel quality), hydrotreating (which reduces sulfur, nitrogen and oxygen content) and hydrocracking (converting heavy crude oil fractions into light oils and gasoline). Most of the hydrogen is used by the companies that produce it, and only a small portion is traded on the market. Both the hydrogen plants and the industrial facilities that use them are usually in the same location. This is due to the technical difficulties involved in transporting hydrogen.

Technological environment of hydrogen production in Poland

A report analyzing the value chain of the hydrogen economy in Poland (Tchorek et al., 2023a) outlines the low CO recommended by the European Union$_2$ and the methods currently used to produce hydrogen in Poland. Among them were such methods as: electrolysis from RES (wind farms, photovoltaics), electrolysis from the grid, electrolysis from nuclear energy, steam reforming of natural gas, steam reforming of biogas, coal gasification, pyrolysis of natural gas, waste processing, thermochemical processes, biomass gasification, and other methods at the stage of technological development with a commercialization date that is difficult to determine (hydrogen separation membranes, photolysis, dark fermentation of biomass, biological processes, water deoxidation). Their characterization and assessment of their applicability in the light of the provisions of EU policy documents and national acts is based on a comparison of the volume of CO_2 emissions during hydrogen production, the established level of technological readiness (TRL) of a given method and the averaged cost of *hydrogen* production in EUR/1kg H_2 (*Levelized Cost of Hydrogen*, LCOH). The various methods are discussed in great detail in the aforementioned report, for this only the most important findings on hydrogen production methods in Poland and their prospects in the coming years will be given here. The choice of hydrogen production methods used now and in the future is, of course, influenced by the regulatory environment, which consists of strategic documents and directives of the European Union and Polish legal acts, which include:

- RED Directive with Delegated Acts,
- EU taxonomy with delegated act
- New Gas Package
- REPower EU
- Net Zero Industry Act
- others: EU ETS, CEEAG
- selected national acts.

Hydrogen production in Poland and its methods are also affected by factors related to the market environment, which determine such determinants as:

- Natural gas price fluctuations,
- Electricity price fluctuations,
- The cost of producing electricity from RES,
- Electrolysis market development,
- Development of the *Carbon Capture Storage* (CCS) and *Carbon Capture Utilization* (CCU) market - technologies that capture CO_2 emissions in gas reforming,
- The existence of exemplary large-scale low-carbon hydrogen production projects,
- The impact of state regulation on the economic efficiency of hydrogen projects.

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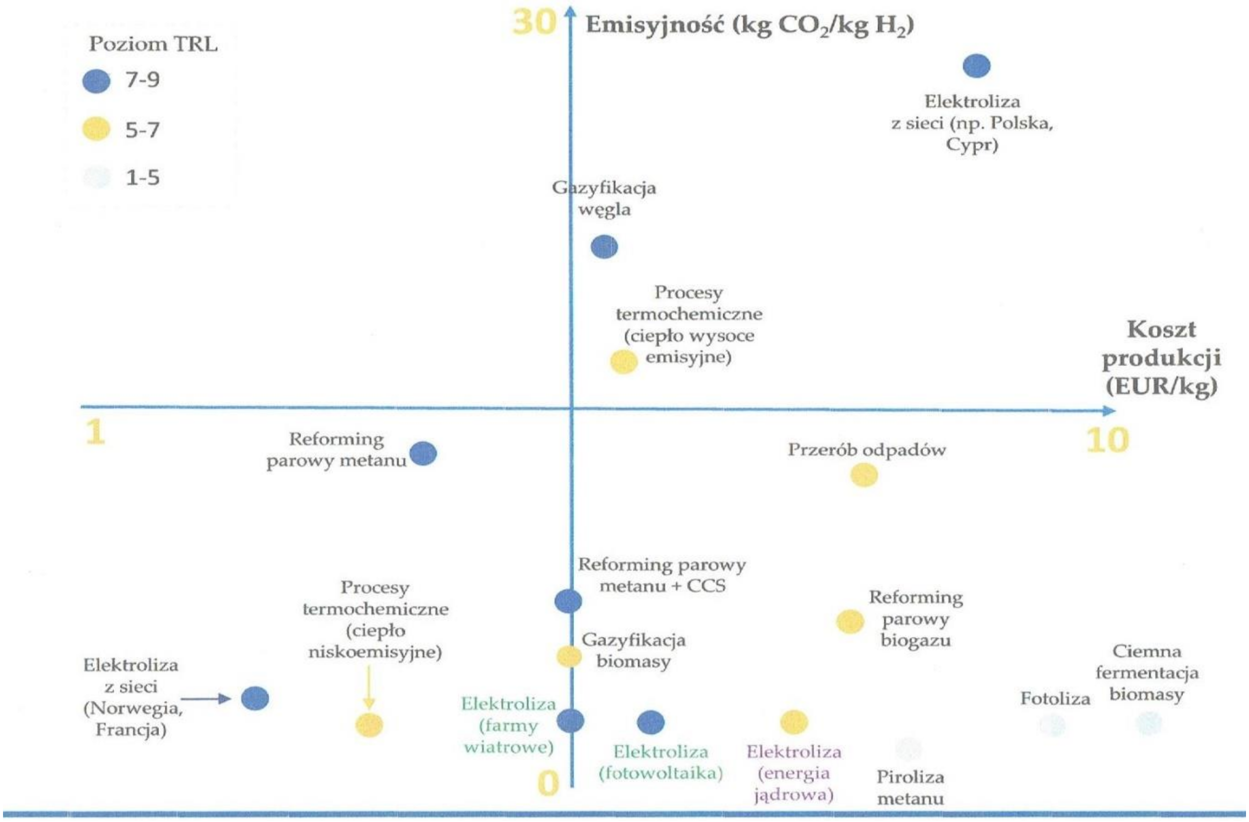
Synthesizing the assessment of various more and less advanced technologies (technology-ready on a scale of 1-9) for hydrogen production with an indication of their emissivity and average cost of hydrogen production is Figure 5. The TRL level of technological readiness includes a 9-stage classification for determining the technological maturity of a process (possibly a product or service) from basic research (TRL 1-2), through conceptual and laboratory work corresponding to industrial research (TRL 3-6), prototype creation in development (TRL 7-8), to a finished solution (TRL 9) applicable in practice.

Figure 5 has two axes - the vertical axis indicates the amount of CO_2 emissions during hydrogen production by a given method, and the horizontal axis indicates the amount of averaged cost of hydrogen production using a given technology. The technology readiness level (TRL) is shown by tri-colored circles. The darker the circle, the more developed the technology is and ready for use in hydrogen production. A very light gray circle indicates a low TRL and a hard-to-find time for a given technology to come to market and be used in Poland for hydrogen production. These methods are currently at the stage of basic research.

The authors of the report pointed out that the hydrogen economy in Poland should be based on low-carbon and renewable hydrogen production, making it possible to create a low- and zero-carbon economy. However, it should be noted that not every method included in Figure 5 (including those favored by the European Union's strategic documents based on electrolysis) can be applied in Polish conditions in the coming years for environmental (emissions), economic, legislative impediments or problems with the level of technological readiness.

Electrolysis from the grid in the case of Poland is an expensive and highly carbon-intensive method of producing hydrogen. This makes it unsuitable for use. Coal gasification, steam reforming of natural gas are high-technology and not very costly methods, but due to their relatively high emissivity, they should be used together with CO capture facilities2 (CCS/CCU) to meet EU climate policy requirements. The European Commission's recommended method of hydrogen production based on electrolysis from RES (wind farms and photovoltaics) has a TRL of 7-9 and is still developing, with costs still being optimized. It has the advantage of very low CO_2 . In contrast, biogas steam reforming and waste treatment are considered promising (still developing) complementary methods, with potentially low cost of hydrogen production. Unfortunately, their use leads to CO emissions$_2$, which would need to be reduced in the long term.

Figure 5: Matrix of hydrogen production methods



Source: Tchorek et al. (2023a), p. 11.

It is difficult to consider today that the electrolysis method from nuclear power for the production of so-called "purple hydrogen" can be used in Poland in the relatively short term due to the lack of large nuclear units and SMRs. Although the TRL level is estimated at 6-7 and the emissivity of the hydrogen production process is close to zero, the lack of developed nuclear power and the high cost of hydrogen production are the biggest barriers to the use of this method in Poland in the coming years.

The authors of the cited report prepared some conclusions and recommendations for policymakers, the implementation of which should support the hydrogen economy at the production stage. Among them were the following statements (Tchorek et al. 2023a, p. 39):

- it is necessary to launch a support system for the production of renewable hydrogen and derivatives in Poland (RFNBO) - in Poland, only hydrogen produced from RES will make it possible to meet the RFNBO targets;
- It is necessary to enable industrial RES investments using direct lines;
- The state should analyze the possibility of introducing regulatory and/or network fee concessions for hydrogen producers (this would slowly reduce the cost of producing hydrogen by 1-2 EUR/kg);
- the approach should be promoted and supported in energy and hydrogen projects that the RES plant is a component of the hydrogen production system, not an independent asset on which maximum profit must be made (buying electricity for the electrolyzer at wholesale or indexed to wholesale prices will make the renewable hydrogen market unprofitable for a long time to come);
- Industrial companies using hydrogen in technological processes should consider the impact of the revised 2023 EU ETS/CBAM on the unit cost of producing 1kg of hydrogen; these may increase significantly by 2030 due to the increase in the price of CO allowances$_2$ (160 EUR/t CO_2 in 2030), the entry of hydrogen into CBAM from 2026 and the gradual move away from free allocation, the tightening of sectoral CO2 benchmarks for hydrogen production in the EU ETS;
- it is necessary for the state to strategically plan the connection and construction of RES installations exclusively for hydrogen production in Poland at the level of the National Energy and Climate Plan 2021-2030 (NERP) and the Energy Policy of Poland until 2040 (PEP2040), rather than for the needs of the electric power industry and wholesale energy sales.

Hydrogen storage as a link in the value chain of the hydrogen economy in Poland

A number of factors influence the hydrogen storage processes in Poland and the methods used now and in the future - hydrogen hydrogen characteristics and storage requirements, technological, regulatory and economic considerations. As indicated by Folentarska et al. (2016) "Due to the properties of hydrogen, i.e. low energy density compared to conventional fuels, flammability and high explosiveness, hydrogen storage materials should be distinguished by high hydrogen storage capacity, technological simplicity, efficient hydrogen absorption/desorption cycles, low price and safety of use" (Folentarska et al., 2016, p. 125).

Hydrogen storage is subject to regulatory actions determined by EU and national legal acts, such as: delegated acts to the European Union Taxonomy (defining the rules for counting investments in hydrogen storage as compliant with the Taxonomy and making a significant contribution to mitigating the climate effects of global warming), the Package for Decarbonization of the Natural Gas and Hydrogen Market (the so-called New Gas Package), and national legal acts on hydrogen production and their amendments, including the Energy Law and the Geological and Mining Law. New Gas Package), as well as national legal acts on hydrogen production and their amendments, including the Energy Law, the Geological and Mining Law, and regulations on detailed conditions for operation of the hydrogen system (Tchorek et al, 2023a).

Hydrogen is a very common element with a high gravimetric density and a low volumetric density at the same time. It is the lightest element in the universe. This necessitates its storage under room conditions (at room pressure and temperature) over very large areas. As indicated by Siekierski et al. (2023) it has in gaseous form the highest molecule velocity, resulting in a high diffusion coefficient, as well as the highest thermal conductivity and lowest viscosity. Molecular hydrogen has the highest heat of combustion of all fuels known to date, with no direct emission of carbon dioxide.

The volume density of hydrogen gas at ambient atmospheric pressure is about 0.09 kg/m³. Compression to 350 bar causes an increase in volumetric density to a value of 23 kg/m^3 , and compression to 700 bar causes a further increase in volumetric density to a value of 41 kg/m^3 . This allows 5 kg of hydrogen to be stored in a 125-liter fuel tank. A 300-liter tank allows storing 13-15 kg of hydrogen at 700 bar. Compressing hydrogen from 20 bar (the output pressure from an electrolyzer or reformer) to a pressure of 700 bar requires up to several kWh of electricity for every 1 kg of hydrogen. The energy consumption of the compression method results in a loss of primary energy of hydrogen of up to about 10-15%. At the same time, it should be remembered that liquefied hydrogen has a high volumetric energy density of 71 kg/m^3 at an ambient pressure of 1 bar. This value is almost double that of hydrogen compressed to a pressure of 700 bar (Tchorek, 2022). Gaseous hydrogen can be compressed to high pressure to increase its energy density (de Jongh, Adelhelm, 2010).

Hydrogen storage can occur at any stage of the hydrogen economy value chain from the time the hydrogen is produced until before it is used. This link in the value chain plays an important role in ensuring a stable supply of hydrogen to the industrial, transportation, energy sectors and thus a stable operation of the energy system in the event of an increase in the share of renewable energy sources in the grids.

Hydrogen can be stored in gaseous, liquid and solid form, and the storage process can be classified into two categories - underground (geological) and aboveground (reservoir). The gas can be stored directly in the form of a derivative (hydrogen derivative) and in different states of aggregation, as determined by the purpose of storage and what sector the hydrogen is to be used in (Table 2).

Table 2. Methods of storing hydrogen in different forms of aggregation

<table>
<tr><th colspan="3">Gas form</th><th colspan="3">Liquid form</th><th colspan="2">Permanent form</th></tr>
<tr><td rowspan="3">Compre-sated hydrogen</td><td colspan="2">Synthetic hydrocarbons:</td><td rowspan="3">Liquid hydrogen</td><td>Chemical Hybrids:</td><td>LOHC:</td><td>Metal hydrides:</td><td>Porous materials:</td></tr>
<tr><td rowspan="2">Compre-sed methane</td><td>Liquid SNG</td><td>Ammonia</td><td>MCH</td><td>Boro-water</td><td>Graphene</td></tr>
<tr><td>Synthetic gasoline</td><td>Methanol</td><td>DBT</td><td>Type-AB alloys</td><td>Aerogel carbon</td></tr>
</table>

		Synthetic disel		*Isopropa-nol*	*Benzene*	*Aluminu m hydride*	*Nano carbon tubes*

Source: Tchorek et al. (2023).

Hydrogen storage methods can also be divided into physical and material methods, as shown in Figure 6. Physical methods include compression and liquefaction of hydrogen. At present, these methods are the easiest to implement and more common, but they have many technical shortcomings, according to experts. In contrast, material methods are based on physicosorption and chemisorption processes and, according to experts, are almost free of drawbacks (Mohan et al. 2018). Unfortunately, research and development processes in this area are still ongoing, which means that they cannot be put into widespread use at present (Kozikowski, Szymlek, 2022).

The aforementioned report on the value chain of the hydrogen economy in Poland discusses the various methods of storing hydrogen in different forms of aggregation and two variants - above-ground and underground (Tchorek et al., 2023a). Hydrogen in gaseous form can be stored underground in salt caverns or rock caverns, at sites left over from depleted gas deposits. On the other hand, pressurized tanks are used for storing this gas on the ground, which is currently the most popular form of hydrogen storage with a TRL of 9, although the storage capacity in tank form is very small (1.1 t of hydrogen). Composite or steel tanks can come in stationary form (e.g., at industrial installations), or mobile form (e.g., for intermodal transport).

Each of the listed methods of hydrogen storage in Poland has different characteristics - a different level of technological readiness and storage capacity, as well as requirements in terms of storage pressure, constant volume of gas in storage, and, in the case of underground hydrogen storage, also the depth of storage.

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Figure 6: Classification of hydrogen storage methods

Source: Kozikowski, Szymlek (2022), p. 16.

Poland has a large potential for hydrogen storage in the form of salt caverns located onshore, which are characterized by greater flexibility compared to storage after depleted gas fields and saline aquifers. This is due to the possibility of performing several injection and withdrawal cycles in them during the year, making it possible to respond to changes in the market situation. Caverns near the coast (up to 50 km from the shore) could be used as storage facilities for imported hydrogen. The advantages of this storage method include the fact that salt caverns have a high level of technological readiness (TRL is 8-9), a low risk of hydrogen contamination and high storage efficiency (98%), and a large storage capacity (300-120,000 t of hydrogen).

For liquid and solid hydrogen storage, liquid hydrogen (TRL is 7-9) and ammonia (TRL is 9) are considered the most common and developed methods. These are mature tank technologies for small and medium scale storage for liquid hydrogen and large scale for ammonia. However, they have some disadvantages, including the flammability of the stored substance and high energy consumption for liquid hydrogen and medium for ammonia. Some advantage of these methods is the medium flexibility of the storage system, which can be useful in situations of changing hydrogen demand. The liquid hydrogen (LOHC) tank storage method has a much greater ability to respond flexibly to market changes. It requires carbon management, low energy consumption, but its disadvantage is also the flammability of the stored substance. Currently, this method has a medium level of technological readiness and commercialization (TRL is 6-8), which hinders its availability in Poland. A similar problem exists with the aluminum hydride method. Although this storage method protects against the flammability of the substance, it has an even lower level of technological and commercial readiness and low flexibility of the storage system.

Medium- and long-term storage of hydrogen and the energy it contains is indicated as one of the most important goals for the development of a hydrogen economy in each EU member country. The growing consumption of hydrogen for energy purposes will force the need not only for its production, but also for storage. This, in turn, contributes to the need for investment activities in hydrogen infrastructure. According to experts, investment in hydrogen storage infrastructure can be as much as 30% of the total infrastructure costs of the hydrogen economy value chain (IEA, 2023). The development of the hydrogen market will encourage the emergence of entities offering underground hydrogen storage services in countries with better geological conditions. This represents an opportunity for Poland, which has significant potential for storage using salt caverns. This method offers the lowest averaged cost of storing 1 kg of hydrogen with high storage potential.

Expert analysis shows that depleted gas fields have the greatest hydrogen storage potential, but this is currently the least mature of the technologies analyzed. It should also be remembered that the use of the various available methods is determined by the planned period of hydrogen storage. For seasonal storage of large quantities of hydrogen, depleted gas fields can be used. For monthly periods, salt caverns and ammonia tanks can be used. For storage of hydrogen on a weekly or daily basis, storage in the form of pressure vessels and liquid hydrogen tanks are proposed. On the other hand, storage in lined rock caverns, which can be used to store hydrogen for several months, but have a medium capacity, is indicated as an intermediate method (Tchorek et al., 2023a).

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Taking into account the pros and cons of various storage methods, the development of technology in this area to date, and the geological potential of Poland, the following conclusions and recommendations can be made for this link in the value chain of the hydrogen economy in Poland (Tchorek et al., 2023a):

- Barriers to the development of the hydrogen economy in Poland in the coming years will become the need to ensure an adequate number and size of storage facilities for hydrogen, as well as to guarantee sufficient amounts of electricity from renewable energy sources for renewable and low-carbon hydrogen production;
- it is necessary for the state to stimulate the development of both large-scale hydrogen storage in geological structures and smaller aboveground storage facilities; each of these types of storage facilities must perform different roles, so both types are needed for the development of the hydrogen economy;
- important for the development of future transportation infrastructure based on hydrogen energy is the availability and deployment of storage facilities within the country; this is particularly important in the context of the location of high-voltage transmission networks and large-scale storage facilities in geological structures;
- strategic and regulatory policies introduced by the state should take into account, increasing legal obligations for the use of renewable hydrogen from 2030; this will enforce the possession of hydrogen reserves in Poland, while helping to ensure the country's independence and strategic-industrial security;
- it is necessary to take advantage of Poland's favorable geological conditions and its considerable potential for hydrogen storage in salt caverns on a European scale; this will enable greater independence in storing hydrogen in the country, but also provides an opportunity to provide hydrogen storage services for other customers (from EU countries).

Hydrogen transportation

The next link in the value chain of the hydrogen economy in Poland should be considered in the context of the impact of technological, regulatory and market conditions. These determine not only the choice of a particular mode of hydrogen transportation, investments related to

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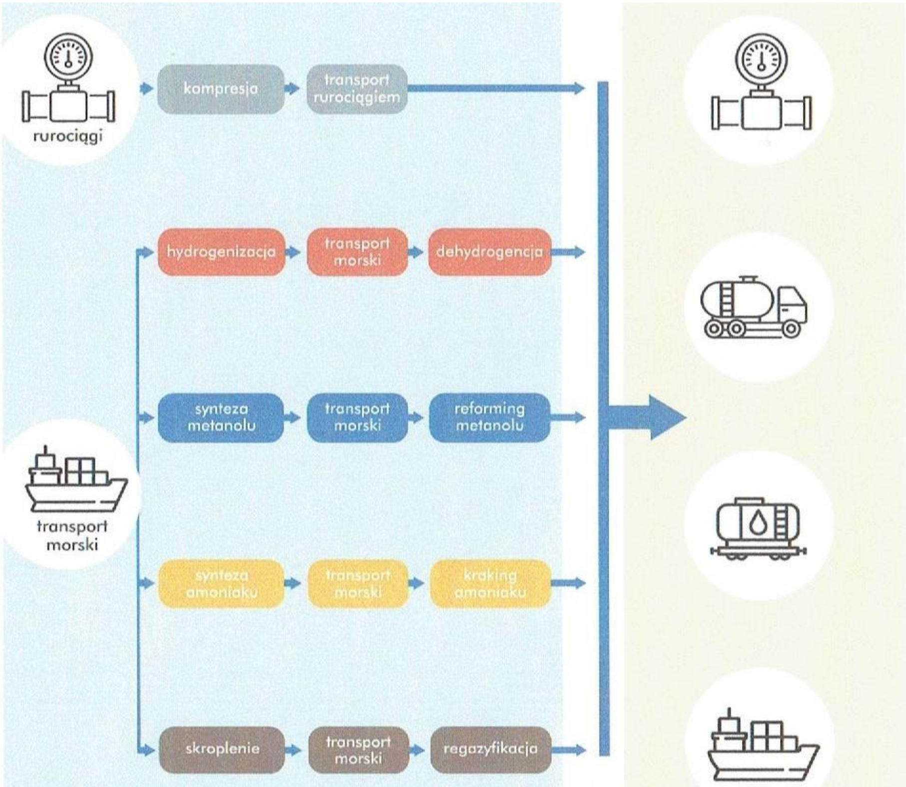
the development of transport infrastructure, but also the efficiency of the process due to the average cost of transporting 1 kg of hydrogen.

The main elements of the hydrogen transportation value chain and their use depending on the distance the hydrogen must travel (above or below 500 km) are shown in Figure 7.

Figure 7: Types of hydrogen transport



Source: Tchorek et al. (2023b), p. 18.

Long-distance transportation of various forms of hydrogen - at distances up to and above 500 km - can be carried out either by pipeline, or by sea transport. In the case of the latter method, further processing of the various forms of hydrogen transported must be taken into account in order to continue its distribution over distances of less than 500 km (via pipelines, road transport, tankers, rail and sea transport, intermodal).

The listed hydrogen transportation technologies have different levels of technological readiness, as discussed in detail in the cited report. Its authors (Tchorek et al., 2023b) indicate that the TRL varies depending on the scale of the infrastructure. For large-scale

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transportation (> 1000 t H_2 per day), none of the indicated methods reached TRL 9 across the entire chain. The most technologically advanced method in the case of maritime transport is currently the method of transporting hydrogen in the form of ammonia in the situation of increasing the scale of maritime units for its transportation. The lowest level of technological preparedness is in the case of maritime transportation of hydrogen in the form of LOHC and methanol. The competitiveness of methanol and ammonia as hydrogen carriers is limited by the need for reconversion to obtain hydrogen again, which requires the consumption of significant amounts of energy. However, removing the need for reconversion and using direct liquid forms of hydrogen improves the attractiveness of these transportation methods (Tchorek et al., 2023a).

For pipeline transport, the technology readiness level is relatively high, although it varies depending on the method. In the case of using a dedicated pipeline, the TRL is 8-9, but the existing technology would require an increase in the scale of hydrogen transportation and the use of higher capacity pipes. The same level of technology readiness is present in the case of pipeline retrofits, but if this method were to be used to transport hydrogen, three times more powerful compressors would be required. The ammonia injection technology has a TRL of 8 and requires a larger scale application for transporting hydrogen in large quantities. In contrast, the transportation of ammonia by pipeline alone is a mature technology (TRL is 8-9) and serves the needs of specialized industrial customers.

Compressed hydrogen pipelines (dedicated / retrofit of the gas network) can be used to transport hydrogen over distances of less than 500 km, but also intermodal transport of hydrogen in compressed and liquid form. Taking into account the technological peculiarities and the vulnerability of the infrastructure to various unpredictable events (natural disasters, assassinations, military actions), the transport of hydrogen in liquid form through pipelines is not currently a solution for larger-scale application. However, it can be noted that the greater the distance of hydrogen transport and the increasing needs associated with increasing the volume of hydrogen delivered, the greater the attractiveness of pipeline transport relative to intermodal transport, especially road transport. Transport of compressed hydrogen allows for increased transportation flexibility due to the possibility of intermodal solutions through the use of containers. Taking into account the higher density of hydrogen in liquid transport, this method becomes more competitive as the distance and amount of hydrogen transported increases (Tchorek et al., 2023a).

When considering the use of different types of hydrogen transportation in Poland, the cost of transporting or shipping hydrogen should also be taken into account. Experts point out that the methods and costs of hydrogen transportation are related to the scale of the hydrogen market (the annual volume of production, the possible volume and directions of hydrogen imports and the density of sales markets). The larger the scale of this market, the lower the average hydrogen transportation costs. In order to make a detailed calculation of transportation costs for the Polish hydrogen market, it would be necessary to adopt specific data for a selected business case. This is due to the fact that the costs of hydrogen transportation at the early stage of market development vary strongly depending on the size of the investment and its infrastructure environment (Tchorek, 2022).

Researchers involved in the development of the hydrogen economy in Poland believe that at the beginning of the development of the hydrogen market with small volumes of hydrogen production, the cheapest way to transport it for short distances of less than 200-300 km will be to transport hydrogen gas in tanker trucks. With the emergence of a more mature and developed market, such modes of transportation as transportation in tank cars of medium volumes of liquefied hydrogen production over distances of 300-500 km, within several provinces, and pipeline transportation of large volumes of hydrogen over distances of more than 300 km, within several provinces or across borders, will become cost-effective (Tchorek, 2022).

Poland's use of the hydrogen shipping method is currently very expensive. The unit cost of transporting hydrogen by this method is about 6 times more expensive than transporting LNG. If the use of sea transportation is pursued, it will be necessary to increase the scale of operations to take advantage of economies of scale for cost optimization. This will be necessary in the situation of hydrogen imports, but to handle the hydrogen trade Poland needs to create the appropriate infrastructure - build a hydrogen terminal (similar to an LNG terminal). Experts also point out that there are technological possibilities for handling LNG and hydrogen supplies within a single gas port (Tchorek, 2022).

As part of the development of the hydrogen economy in Poland, in addition to the transportation of hydrogen, it is necessary to remember the need to create a proper infrastructure for supplying transportation means with hydrogen as an alternative fuel. This is regulated by the Regulation of the European Parliament and the Council of Europe on the Development of Alternative Fuel Infrastructure (AFIR) (THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION, 2023). AFIR replaces Directive 2014/94/EU of the European Parliament and of the Council of October 22, 2014 on the development of alternative fuel infrastructure. The new legislation will come into force on April 13, 2024. The regulation is part of the *Fit for 55* package and sets out specific steps for the creation of charging infrastructure for alternative vehicles, including those powered by hydrogen. It indicates that there should be stations for charging BEV road vehicles with electricity and vessels in ports and aircraft in summer resorts, refueling FCEV road vehicles with hydrogen, and refueling road vehicles with liquefied methane. The TEN-T Trans-European Transport Network, which is considered a comprehensive network and includes major trans-European highways and 424 urban nodes, was taken as the starting point for this regulation. It has been assumed that by 2030 there will be at least 1 hydrogen refueling point at an urban node every 200 km on the main roads of the TEN-T core network. The minimum capacity (efficiency of the point) should be 1 t of hydrogen per day at a pressure of 700 bar. In addition to this, the hydrogen refueling infrastructure should allow ad hoc refueling, electronic payment and clearly inform about payment options. This means that a total of 49 hydrogen refueling stations must be built in Poland by 2030 - 30 stations in urban hubs and 19 stations along the roads of the TEN-T core network. This represents a major challenge for Poland's hydrogen economy.

Taking into account the level of development of available hydrogen transportation technologies, regulatory requirements and market conditions (the relationship of demand and supply in the hydrogen market, the average cost of transporting 1 kg of hydrogen depending on the method of transportation), the following conclusions and recommendations can be made for this link in the value chain of the hydrogen economy in Poland:

- Insufficient supply of hydrogen for domestic demand for this energy source and the inability to ensure self-sufficiency in this area during the transformation of the gas sector, with insufficient renewable energy sources will force the state to determine the size of the necessary hydrogen imports and possible directions,
- Adequate plans for the development of the port infrastructure network will be necessary in connection with the needs of future maritime transport of hydrogen and its derivatives; before that, it will be necessary to determine the national needs for current and projected use of hydrogen, which will directly affect not only the volume of supplies, but also the choice of mode of transportation for importing hydrogen due to the possibility of direct use of the derivative in certain sectors of the economy (e.g., refining, petrochemical, fertilizer);
- The creation of a dedicated support system for the import of green hydrogen and its derivatives is recommended, and the solution used by Germany (H2Global platform) and the Netherlands is cited as an example of good practice in this regard;
- The retrofitting of gas networks and their conversion to hydrogen, despite being the most attractive in terms of cost, may be limited due to the need to adapt infrastructure at customers enabling the use of hydrogen,
- A barrier to the transportation of hydrogen may become its distribution to the end user, which will be determined by the amount of distribution costs; these may be lowered by creating local centers to balance demand with generation capacity;
- The operation of hydrogen valleys should have a positive impact on lowering distribution costs and reducing the price of hydrogen at the hydrogen end-user; they will also contribute to reducing the carbon footprint of the hydrogen supplied.

The use of hydrogen in the Polish economy

Hydrogen is currently used in such sectors as the chemical, refining, petrochemical, steel and metallurgical industries, and the food industry. The chemical sector uses hydrogen in the production of fertilizers (primarily ammonia), methanol, oxidized water, followed by methanol, caprolactam (plastics production) or oxo alcohols (production of detergents, solvents, plasticizers and paints, plastic packaging). The operation of the chemical sector is based on the synthesis of ammonia, which requires a reaction between hydrogen and nitrogen. Ammonia production primarily uses gray hydrogen, which comes from steam reforming of natural gas. In Poland, the chemical industry could significantly reduce CO_2 emissions by using less emissive types of hydrogen (blue, purple and green). Experts indicate that the use of RFNBO (green hydrogen) and low-emission fuels could significantly reduce the carbon footprint of the chemical sector in Poland (EY, 2023).

In the case of the refining industry, hydrogen is used, among other things, in processes to remove sulfur, nitrogen and other impurities from crude oil and natural gas. It is also a feedstock in the hydrocracking process, during which it is used to convert heavier fractions of crude oil into lighter products such as gasoline and diesel fuels. For this process, gray hydrogen from steam reforming of natural gas or waste hydrogen from technological processes is used. Hydrogen can also be used in the production of so-called synthetic fuels as new refinery products (Brodacki et al., 2021; Tchorek et al., 2023b). In Poland, the use of RFNBO fuels and low-carbon hydrogen in refinery processes would make it possible to reduce the sector's CO_2 emissions and reduce the vulnerability of its players to rising emission allowance prices.

The petrochemical industry uses hydrocarbons to produce organic chemicals and polymers (kerosene, gas, ethane, LPG, natural gas, among others). As indicated by Tchorek et al. (2023), green hydrogen can be used in petrochemicals as a feedstock in steam crackers or as an energy carrier in high-temperature processes (e.g., a cracker burner), reducing the carbon intensity of the process. They suggest that it will be possible to use renewable methanol (a form of hydrogen) during the production of organic chemicals. Besides, the petrochemical sector could also use low-carbon fuels derived from waste hydrogen using CCS technology. The Global Hydrogen Council indicates that the global use of renewable hydrogen in the petrochemical sector could lead to a reduction in CO2 emissions of at least 30% by 2050 (Global Hydrogen Council, 2017). Thus, CO reductions can also be expected in $Poland_2$ after increasing the use of RFNBO fuels.

Nowadays, hydrogen is also used in metallurgy, especially in steel production. Wanting to decarbonize the metallurgical sector would require the use of RFNBO fuels. The process of iron ore enrichment by hydrogen reduction is a potential alternative to traditional methods, which can reduce CO_2 emissions by 70-90% compared to conventional steelmaking processes (EC, 2018).

The food industry uses hydrogen for industrial food production processes and as a packaging gas. Among other things, it is used for the hydrogenation of vegetable fats, which makes it possible to create solid fats with certain properties, such as margarine and frying fats. The process makes it possible to obtain products with the desired consistency and a longer shelf life. In addition, hydrogen is often used as a protective gas in food packaging (protecting food products from oxidation and extending their shelf life). It is also used to extend the freshness of certain products, such as meat and seafood (inhibiting bacterial growth).

In the future, hydrogen can be used in Poland as an energy carrier and storage, which will make it possible to stabilize the electricity system and its balancing when the share of renewable energy in the energy mix increases. These tasks will be carried out primarily in a long-term (seasonal) model, and less frequently in a short-term (hourly/daily) model. A competing technology to the use of hydrogen for energy storage will be battery systems, especially for short-term needs.

Another area of hydrogen use in Poland in the future will be such gas unit-based sectors as power generation, heating and cooling. Regulatory requirements for decarbonization will force gas units to use low-carbon and renewable gas blends, or adapt them to work with CCS-based equipment.

An obvious area of application for hydrogen in the Polish economy is light and heavy wheeled transportation, as well as sea and air transport. Currently in Poland, the use of hydrogen propulsion is being tested in public transport buses in Poznan and Krakow. Hydrogen-powered technologies for small vehicles (passenger or small delivery vans) are already mastered and gradually commercialized in other countries, such as Germany (cabs in

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Hamburg). The development of hydrogen-based road transportation requires the construction of refueling infrastructure according to the recommendations of the AFIR regulation.

Commercialization of the use of RFNBO fuels for light vehicles could occur as early as 2025. Slightly later , between 2025 and 2030, it is suggested that green hydrogen fueling technology for heavy wheeled transport (trucks, buses, rail) will be introduced to the market. Hydrogen and derivatives are a good source of propulsion for long distances, the need for continuous operation and short refueling times, as well as maximizing the permissible weight of cargo carried.

In the case of the use of hydrogen in maritime and air transport, experts indicate that the commercialization of the application may not take place until 2030-2035. The decarbonization of these sectors of the economy in the medium to long term will be carried out using hydrogen derivatives, i.e. renewable ammonia, renewable methanol, synthetic fuels such as e-kerosene.

Analyzing the potential directions of hydrogen application in the Polish economy, Tchorek and his team (Tchorek et al., 2023) formulated the following conclusions and recommendations.

- it is necessary to include RFNBO fuels in detail in Poland's energy policy (PEP 2040, NERP) as factors for decarbonizing sectors that are difficult to electrify directly (e.g., chemical industry, refining, metallurgy, heavy transport, maritime, aviation).
- the most important factor in ensuring the profitable use of RFNBO fuels will be the optimization of the cost of obtaining electricity; this necessitates carrying out the liberalization of the energy market in Poland (direct line, dissemination of PPAs, reductions in regulatory and network fees for hydrogen valleys, energy storage),
- Supporting the increased use of green hydrogen will be EU policy - its regulations are gradually eliminating fossil fuels from the market while promoting their substitution with RFNBO fuels,

- The answer to increased hydrogen consumption must be a greater supply of low- and zero-emission hydrogen, and this requires the introduction of a regulated support system to cover the financial gap between the cost of the RFNBO fuel and the price of its direct reference carrier (e.g., natural gas or diesel); experts suggest that in the first phases of market development (when there is no wholesale market), the support system should ensure the pooling of hydrogen producers and consumers, which will reduce the risk of system imbalance;
- The use of RFNBO fuels in the Polish economy will enable the decarbonization of the Polish economy and reduce Poland's exposure to the EU ETS, including the rising price of CO emission allowances$_2$.

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Summary

Poland is one of the leaders in hydrogen production in Europe and the world (3rd in Europe and 5th in the world). Unfortunately, this is gray hydrogen production, realized mainly for the companies' own needs. With the acceleration of the green economy in the EU, Poland also faced the need to develop a hydrogen economy in the coming years. Hydrogen technologies for the entire value chain of the hydrogen economy are undoubtedly now one of the main priorities, enshrined in EU and national strategic documents. They are also the subject of research and analysis by representatives of academia, business and governments of many countries. However, it is still an area with a still relatively low level of development, which faces many barriers. This is particularly evident in Poland. Among the most important barriers and challenges to the development of the hydrogen economy in Poland diagnosed in a survey conducted in 2023 among a group of 34 entities belonging to various sectors related to its value chain, experts, representatives of hydrogen valleys mentioned (Tchorek et al., 2023):

1. Poland lacks systemic support dedicated to renewable hydrogen and derivatives (covering the financing gap, long-term off-take),
2. impediments related to the lack of an adequately developed and regulated electricity system in Poland (including a lack of regulations for direct lines, a poor PPA market, a highly carbon-intensive energy mix, grid and RES connection problems),
3. Lack of transmission, distribution, storage and terminal infrastructure, making it difficult to create a liquid wholesale market and connect the demand and supply sides,
4. Lack of adequate regulations in Poland dedicated to renewable hydrogen and derivatives (difficulty in implementing investments, especially at the administrative and environmental level),
5. Lack of a clearly defined strategic vision for the development of the hydrogen economy (update of the PSW, PEP2040, KPEiK in terms of hydrogen).

Although the respondents did not point to a competence gap as a barrier to the development of the hydrogen economy in Poland, it should be noted that currently Polish society and potential cadres for this economy are not yet prepared to participate in such a huge green transformation. As PARP experts point out, "It is necessary to include the needs of the Polish economy in the area of hydrogen technologies in the guidelines of the Polish Qualification Framework. Building a hydrogen economy requires strongly specialized and interdisciplinary knowledge. The problem of the Polish hydrogen technology market is the lack of an education system at all levels of the Polish Qualification Framework. This significantly weakens the country's potential to implement groundbreaking R&D projects, as specialists largely have to learn 'on a living organism', i.e., during the implementation of project work itself." (PARP, 2022, p. 194).

Bibliography

1. *Antas Ł., Bocian M., Bajek M., Giers M., Bijoś K. (2021). Hydrogen in Central and Eastern Europe. Development perspectives in the Visegrad Group countries and Ukraine, Esperis, Warsaw.*
2. *IDA. S.A. (2024). Hydrogen Valleys, https://arp.pl/pl/jak-dzialamy/transformacja-energetyczna-/doliny-wodorowe/*
3. *Brodacki D., Gajowiecki J., Hajduk R., Kocejko P., Kowalski S., Mataczyńska E., Miętkiewicz R., Nowakowski R., Plaskiewicz N., Ruszel M., Sienkiweicz M., Skwierz S., Turowski P., Witkowska A. (2021). Green hydrogen from RES in Poland. Use of wind and PV power for green hydrogen production as an opportunity to implement the EU Climate and Energy Policy in Poland, Lower Silesian Institute for Energy Studies, Polish Wind Energy Association, Wrocław 2021.*
4. *de Jongh P.E., Adelhelm Ph. (2010). Nanosizing and Nanoconfinement: New Strategies*
5. *EC. (2018). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52018DC0773.*
6. *EC. (2019). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. The European Green Deal, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640.*
7. *EC. (2020). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. A hydrogen strategy for a climate-neutral Europe, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0301.*
8. *EC. (2021). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS EMPTY. 'Fit for 55': Delivering the EU's 2030 Climate Target on the way to climate neutrality, Brussels, https://eur-lex.europa.eu/legal-content/EN-PL/TXT/?from=EN&uri=CELEX%3A52021DC0550.*
9. *EC. (2022). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. REPowerEU: Joint European Action for more affordable, secure and sustainable energy, COM(2022) 108 final, Brussels, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022DC0108*
10. *Elżbieciak T. (2023). What electrolyzers will produce green hydrogen in Poland?, Wysokie Napięcie.pl, https://wysokienapiecie.pl/82287-elektrolizery-wyprodukuja-wodor-w-polsce/*
11. *EY. (2023). Green hydrogen-a revolution or a passing fad? Opportunities and challenges for the Polish economy, Warsaw.*

12. Folentarska A., Kulawik D., Ciesielski W., Pavlyuk V. (2016). Modern materials for hydrogen storage as fuel of the future, Chemistry. Environment. Biotechnology, No. 19, pp. 125-130.
13. Global Hydrogen Council (2017). Hydrogen Scaling Up: A Sustainable Pathway for the Global Energy Transition, https://www.h2knowledgecentre.com/content/policypaper1201
14. IEA. (2023). Energy Technology Perspectives, https://www.iea.org/reports/energy-technology-perspectives-2023
15. Komorowska A., Mokrzycki E., Gawlik L. (2023). Hydrogen production in Poland - the current state and directions of development, Polityka Energetyczna - Energy Policy Journal, 26(4), pp. 81-98, https://doi.org/10.33223/epj/170913.
16. Kozikowski S., Szymlek K. (2022). Hydrogen - green gold. Safe storage, Electroinstaller, No. 9, pp. 14-21.
17. Kryczka D. (ed.). (2021). Development of the hydrogen economy in the EU and member states - regulatory and financial environment, ESPERIS, UN Global Compact, Warsaw.
18. Łącka I. (2023). The Role of Green Energy in the Economic Growth of the World, in Bąk I., Cheba K., Green Energy. Meta-analysis of the Research Results, Springer, Cham, pp. 41-57.
19. Łącka I., Wojdyła P. (2022). Energy transformation in the shadow of war. EU funding as an opportunity for the development of hydrogen technologies in Poland, Industrial Chemistry, Zeszytowa 2, pp. 80-88.
20. The value chain of the hydrogen economy in Poland. (2023). CIRE.pl, https://www.cire.pl/artykuly/serwis-informacyjny-cire-24/lancuch-wartosci-gospodarki-wodorowej-w-polsce.
21. Mierwinski R. (2022). The green side of business. Hydrogen to the Energy Rescue, https://mycompanypolska.pl/artykul/zielone-strony-biznesu-wodor-na-ratunek-energetyki/8304 (accessed March 12, 2024).
22. Mohan M., Sharma V.K., Kumar E.A., Gayathri V. (2018). Hydrogen storage in carbon materials-A review, Energy Storage, 1:e35, DOI: 10.1002/est2.35.
23. Polish Monitor of December 7, 2021, item 1138 (2021). Polish Hydrogen Strategy until 20230 with an Outlook until 2040. Annex to the Resolution of the Council of Ministers of November 2, 2021 (item 1138).
24. PARP. (2022). Market and technology development map for the hydrogen technology area, Warsaw.
25. Pilszyk, M., Juszczak, A., Gonera, Ł. (2023), Race for hydrogen. Countries and their hydrogen strategies, Policy Paper, No. 5, Polish Economic Institute, Warsaw.
26. Siekierski M., Majewska K., Mroczkowska-Szerszeń M. (2023). Methods for efficient and safe storage of hydrogen as a condition for its widespread use in transport and energy, Nafta-Gaz, No. 2, pp. 114-130.
27. Smoleń M., Żelisko W. (2023). International Dimension of the Polish Hydrogen Strategy: Conditions and Potential for Future Development, RIFS Discussion Paper, June 2023, https://doi.org/10.48481/rifs.2023.019
28. Sobolewski M. (2022). Hydrogen economy. Infos, no. 6(298).
29. Tchorek G. (2022). The hydrogen revolution - how to benefit?, PARP Webinar, Warsaw 18.10.2022, https://www.parp.gov.pl/attachments/article/83293/webinarium_18102022_wodor.pdf
30. Tchorek G., Targowski F., Mikusek P., Grzybowski M., Kupecki J., Hercog J., Skrzypkiewicz M., Niemczyk A., Błesznowski M., Wierzbicki M. (2023a). Value chain of

the hydrogen economy in Poland. Report, University of Warsaw, Institute of Energy, Warsaw.

31. *Tchorek G., Targowski F., Mikusek P., Grzybowski M., Kupecki J., Hercog J., Skrzypkiewicz M., Niemczyk A., Błesznowski M., Wierzbicki M. (2023b). Value chain of the hydrogen economy in Poland. Report digest, University of Warsaw, Institute of Energy, Warsaw.*
32. *THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION. (2023). REGULATION (EU) 2023/1804 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 September 2023 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1804*

Towards Meeting Hydrogen Storage Goals, ChemSusChem, No. 3, pp. 1332-1348.

33. *UN. 2015. transforming our World: The 2030 Agenda for Sustainable Development, Geneva, https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981.*
34. *Eighth Meeting of the Coordinating Council on Water Management. (2024), https://www.gov.pl/web/klimat/viii-posiedzenie-rady-koordynacyjnej-ds-gospodarki-wodorowej.*
35. *Wyszkowski K., Piwowarek Z., Nowakowska M., Pałejko Z., Kryczka D. (2022). Hydrogen law - regulatory environment supporting the development of the hydrogen economy, UN Global Compact, Warsaw.*

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