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Aleksandra Komorowska[1], Eugeniusz Mokrzycki[2], Lidia Gawlik[3]

Hydrogen production in Poland – the current state and directions of development

Abstract: In the era of the fight against global warming and in light of the search for energy with the least possible impact on the environment, interest in hydrogen has become a natural direction of development. Striving for a zero-emission Europe by 2050, the EU promotes low-emission and ultimately emission-free hydrogen for the widest possible use in the economy.

Poland has developed a strategic document specifying the necessary activities for the use of hydrogen in the economy, which should at the same time maintain its competitiveness. Poland is currently the third producer of hydrogen in the European Union, which enables strategic thinking about maintaining Poland as a leading player on the hydrogen market in the long term. Currently, hydrogen in Poland is produced by (usually large) state-owned enterprises for their own needs with only a small margin of its resale. This is conventional hydrogen that is mainly obtained from natural gas. Therefore, it is difficult to talk about the hydrogen market, which must develop so that this raw material can be widely used in many branches of the modern economy. However, this requires taking a number of legislative, research and development and investment activities, as well

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✉ Corresponding Author: Lidia Gawlik; e-mail: lidia.gawlik@min-pan.krakow.pl

[1] Mineral and Energy Economy Research Institute PAS, Poland; ORCID iD: 0000-0002-9604-1071; e-mail: komorowska@min-pan.krakow.pl

[2] Mineral and Energy Economy Research Institute PAS, Poland; ORCID iD: 0000-0003-4080-3660; e-mail: mokrzy@min-pan.krakow.pl

[3] Mineral and Energy Economy Research Institute PAS, Poland; ORCID iD: 0000-0002-2181-5394; e-mail: lidia.gawlik@min-pan.krakow.pl

as directing the national energy transformation to renewable energy sources, which may ultimately reduce the costs of pure hydrogen production.

A number of actions have been taken, but the delay in legislative actions is slowing down the creation of the hydrogen market and is limiting the interest of private businesses in engaging in transformation activities.

Keywords: Poland, hydrogen, production efficiency

Introduction

The acceleration of the European Union's actions aimed at limiting the negative effects of climate change and stopping global warming have resulted in strategies being proposed in several directions. In December 2019, the European Commission unveiled an ambitious initiative, the European Green Deal, with the goal of achieving climate neutrality for the European Union (EU) by 2050 (COM 640 2019). This was followed by an increased interest in fuels, the use of which does not emit CO_2 into the atmosphere. In 2020, the document entitled "A hydrogen strategy for a climate-neutral Europe" was published, which describes the directions in which the use of hydrogen in the economy and industry should be developed (COM 301 2020). Subsequently, hydrogen development strategies have been adopted in many EU countries, where national strategies for the development of hydrogen production and use have begun to appear. Such a document was also created in Poland. On November 2, 2021, the Council of Ministers adopted the document "Polish hydrogen strategy until 2030 with a perspective until 2040" (MC&E 2021).

This study describes hydrogen as a raw material, pointing to the features that distinguish it from other energy sources. It also examines the supply side, focusing on production technologies, their efficiency, and associated costs. The possibilities of using hydrogen are manifold, but the development of the hydrogen economy will require a lot of effort both in the area of technological development and, which at the present stage seems to be extremely important, the development of appropriate legal regulations that will enable the development and safe functioning of the hydrogen market. This article presents the position of Poland in the field of hydrogen production against other European countries.

1. General information about hydrogen

Hydrogen has more energy per unit mass than both natural gas and gasoline, making it an attractive transport fuel. However, hydrogen is the lightest element and therefore has a low energy density per unit volume. This means that larger amounts of hydrogen have to be moved to meet the same energy demand compared to other fuels. This can be achieved, for example, by using larger or faster-flowing pipelines and larger storage tanks. While hydrogen can be compressed, liquefied, or converted into hydrogen-based fuels with higher energy densities, these processes – and any subsequent reconversion – consume energy.

Table 1 shows the basic physical properties of hydrogen and their comparison to other fuels.

Table 1. Comparison of physical properties of hydrogen with other energy carriers

Tabela 1. Porównanie fizycznych właściwości wodoru do innych nośników energii

Property	Unit	Specific for hydrogen	Comparison
Density (in gaseous state)	kg/m^3 (0°C, 1 bar)	0.089	1/10 natural gas
Density (in liquid state)	kg/m^3 (–253°C, 1 bar)	70.79	1/6 natural gas
Boiling point	°C (1 bar)	252.76	90°C below LNG
Energy per unit mass (LHV)	MJ/kg	120.1	3 times more than gasoline
Energy density (ambient conditions, LHV)	MJ/L	0.01	1/3 natural gas
Specific energy (liquefied, LHV)	MJ/L	8.5	1/3 LNG
Flame speed	cm/s	346	8 x methane
Ignition range	vol% in air	4–77	6 x wider than methane
Temperature of self-ignition	°C	585	220°C for gasoline
Ignition energy	MJ	0.02	1/10 methane

Source: IEA 2019.

Energy is a fundamental requirement for human life and global development. In addition, it is a key issue in all discussions and meetings on the development of sustainable energy. Renewable energy sources such as solar, wind, wave and tidal energy are considered to be environmentally friendly. Hydrogen produced under certain conditions may also be considered as such. Hydrogen fuel and its demand are expected to grow exponentially over the coming decades.

Due to the advantages and versatility of hydrogen fuel, in the long term, it will be an alternative to hydrocarbon fuels. Hydrogen is considered to be the most efficient and clean energy carrier, producing water only as a by-product of its combustion. The use of hydrogen fuel as an independent source of clean energy and high energy content compared to fossil fuels is globally recognized. Table 2 presents the energy content of different fuels (El-Shafie et al. 2019). Hydrogen has the highest chemical energy content of all of these fuels.

Table 2. Content of chemical energy in various fuels

Tabela 2. Zawartość energii chemicznej w różnych paliwach

Fuel	Chemical energy [MJ/kg]
Hydrogen	120.0
Natural liquefied gas	54.4
Propane	49.6
Aviation gasoline	46.8
Automotive gasoline	46.4
Automotive diesel	45.6
Ethanol	29.6
Methanol	19.7
Coke	27.0
Wood (dry)	16.2
Biogas	9.6

Source: El-Shafie et al. 2019.

2. Hydrogen production

Currently, hydrogen is primarily produced from fossil fuels. The environmental impact of its production varies based on the method employed. The hydrogen produced is often color-coded using colours of the spectrum depending on the production method, as shown in Table 3 (Wappler et al. 2022).

Hydrogen produced through the coal gasification process is called brown or black hydrogen, depending on the type of coal used. If the hydrogen is produced by the SMR process (*steam methane reforming*), it is referred to as gray hydrogen. Currently, this method is, by far, the predominant source of hydrogen production. Approximately 95% of global hydrogen production comes from the process. This process involves reacting fossil fuels (primarily natural gas), with steam at high temperature to produce hydrogen and carbon monoxide.

Hydrogen can also be produced on an industrial scale as a by-product of certain processes, for example, during the production of caustic soda or by chlor-alkali electrolysis, as well as in the naphtha reforming process in refineries.

In recent years, due to emission reduction targets, new hydrogen colors have been introduced. The most well known being blue and green hydrogen. Blue hydrogen can be considered an extension of gray hydrogen as its production also relies on natural gas. However, the carbon dioxide produced during the SMR process is captured and stored – CCS, instead of being released into the atmosphere.

Hydrogen can also be produced by the electrolysis of water using various energy sources. If renewable energy is used in the electrolysis processes, the hydrogen produced is called green hydrogen. Instead of renewable energy, nuclear energy or mixed grid electricity can also be used for water electrolysis. In this case, the hydrogen is pink or yellow, respectively. Hydrogen can also be produced by the pyrolysis of methane, in which case, it is called turquoise hydrogen.

With the exception of gray and black or brown hydrogen, all other colors of hydrogen are often considered low-carbon hydrogen or carbon-free hydrogen.

Table 3. Colors of hydrogen, its classification, and hydrogen production capacity based on technological processes and raw materials and/or energy sources

Tabela 3. Kolory wodoru, jego klasyfikacja i możliwości produkcyjne na podstawie procesów technologicznych oraz surowców i/lub źródeł energii

Source (raw material)	Method	Color	Classification	Percentage of world production in 2020
Hard coal	gasification	black	high carbon footprint	19
Brawn coal	gasification	brown		
Natural gas	natural gas reforming	grey		59
Diesel fuel	partial oxidation	grey		0.6
By-product	reforming of heavy crude oil	grey		21
	chlor-alkali electrolysis	white	clean (low carbon)	
Natural gas + CCS	reforming of natural gas	blue		0.7
Methane	pyrolysis	turquoise		no commercial scale production
Nuclear power	water electrolysis	pink		
Mixed electric network	water electrolysis	yellow		
Renewable energy	water electrolysis	green	carbon-free (green)	0.03

Source: Wappler et al. 2022; IEA 2021a.

In 2020, hydrogen production in the world reached 90 Mt. Of this, 59% was derived from natural gas, mainly by steam methane reforming (SMR). Another 21% of the hydrogen was generated as a by-product, primarily in refineries during the reforming process of heavy crude oil. Coal also remained an important source for hydrogen production in 2020, while coal methods in hydrogen production accounted for less than 1% of the total hydrogen supply. Hydrogen produced by water electrolysis accounted for only 0.03% of the global supply. The CCS method of CO_2 utilization counts for 0.7% of the total hydrogen production (IEA 2021a).

3. Technological maturity of production processes

Chronologically, the development of hydrogen production processes reads as follows (Campbell 2020):

1. Natural gas reforming:

In the SMR (steam-methane reforming) process, natural gas (mainly methane) under pressure (3–25 bar) reacts with high-temperature steam (700–1,000°C) in the presence of a catalyst in the first part of a two-stage process. In the second stage, the gas mixture is passed through a water-gas conversion reactor with steam and a catalyst. This converts most of the carbon monoxide to carbon dioxide, producing additional hydrogen. Carbon dioxide and other impurities are then removed from the resulting gas stream, leaving mostly pure hydrogen.

2. Coal/biomass gasification:

Coal is an organic hydrocarbon that can be used as a source of hydrogen by gasification to extract hydrogen. Hydrogen is produced by the first reaction of carbon with oxygen and steam at high pressure and high temperatures to produce syngas, a mixture consisting mainly of carbon monoxide and hydrogen. After impurities are removed from the syngas, the carbon monoxide in the gas mixture is reacted with steam in a water gas shift reaction to produce additional hydrogen and carbon dioxide. The hydrogen is removed by a separation system and then the highly concentrated carbon dioxide stream can be captured and stored.

Other raw materials (such as forest or harvest residues and biomass crops) could also potentially be gasified. However, each raw material poses unique challenges with regard to the availability and formation of undesirable substances (e.g. tar, CO and CO_2) that can affect production efficiency and facility maintenance.

3. Electrolysis of water:

Hydrogen can be directly produced from water. This can be achieved by electrolysis, which involves passing an electric current between the positive and negative electrodes through water (containing various catalysts). Electrolysis breaks the chemical bonds present in the liquid water molecule, separating the hydrogen and oxygen atoms into individual gases. The electrolysis process takes place at room temperature. The commonly used electrolyte in water electrolysis is sulfuric acid, and the electrodes are made of platinum (Pt), which does not react with sulfuric acid. The process is ecologically clean as no greenhouse gases are produced and the oxygen produced has further industrial applications. However, electrolysis is a very energy-intensive technology compared to the technologies that use fossil fuels.

There are four main methods of water electrolysis for hydrogen production (Kumar and Himabindu 2019; Campbell 2020):

- Alkaline water electrolysis uses the free ions in alkaline water to conduct an electric current for electrolysis to take place; alkaline cells have an aqueous solution containing about 25 to 30% potassium hydroxide.Proton exchange membrane (PEM) water electrolysis uses a polymer electrolyte in the form of a thin, permeable layer and a platinum catalyst,

- ✦ Solid oxide electrolysis cells (SOEC) or ceramic electrolyte are used to produce mainly hydrogen and oxygen.
- ✦ Microbiological electrolysis cells (MEC) use bacteria that grow in an electrochemical environment to break down organic matter.

Several other processes can also be used to produce hydrogen from various feedstock sources. These processes have recently been developed or are less efficient in terms of the amount of hydrogen produced. These include partial oxidation, pyrolysis, thermochemical water splitting, photoelectrochemical water splitting (PEC), photobiological processes, photo fermentation processes, and membrane gas separation.

Figure 1 shows the technological maturity of various hydrogen production technologies in different periods, ranging from the short term, through the medium term, to the long term.

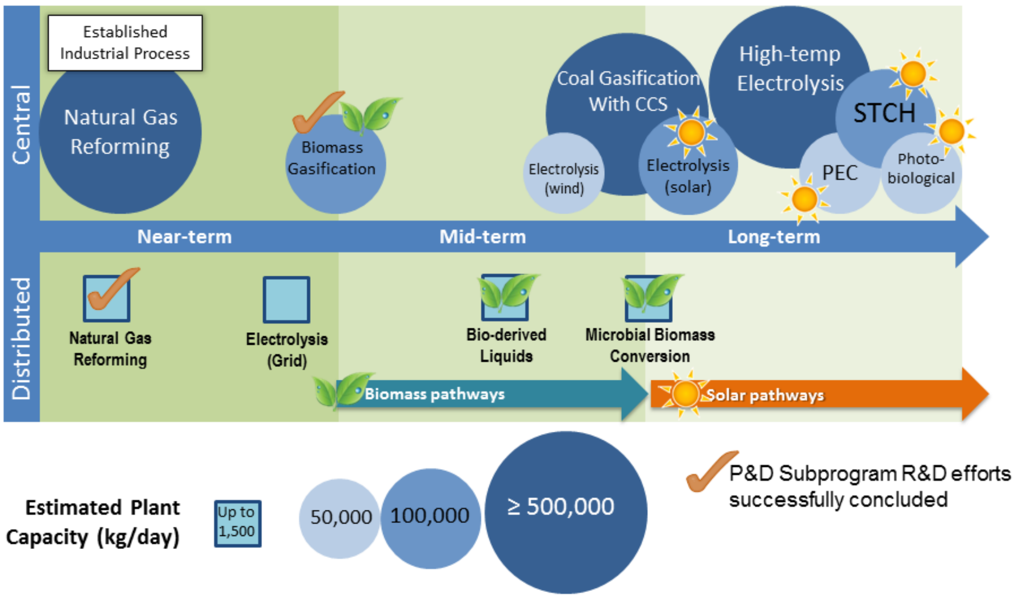

Fig. 1. Hydrogen production technologies – periods and scales of production; hydrogen from thermochemical processes STCH (solar thermochemical hydrogen); photoelectrochemical processes PEC (photoelectrochemical); carbon capture and sequestration (CCS); production and delivery P&D (production and delivery); research and development R&D (research and development)
(Campbell 2020)

Rys. 1. Technologie produkcji wodoru – ramy czasowe i skale produkcji; wodór z procesów termochemicznych STCH (*Solar Thermochemical Hydrogen*); procesy fotoelektrochemiczne PEC (*Photoelectrochemical*); wychwytywanie i sekwestracja dwutlenku węgla CCS (*Carbon Capture and Sequestration*); produkcja i dostawa P&D (*Production and Delivery*); Badania i rozwój B+R (*Research and Development*)

4. Energy efficiency of production

Energy efficiency means the ratio of the output of performance (service, goods or energy), to the input of energy (Directive 2012/27/EU; Gawlik and Mokrzycki 2021b). In the case of hydrogen production under the 'efficiency' term, we understand the amount of energy contained in the produced hydrogen to the entire input of energy used for its production (in %). When it is said that the technology is energy-intensive, it means that the energy efficiency of hydrogen production in this technology is low.

Table 4 presents the latest estimates of hydrogen production costs for selected technologies, as well as the estimated efficiency of these processes. The efficiency of the steam reforming process using the inexpensive natural gas feedstock is a key factor in achieving low-cost hydrogen production. Water electrolysis is a proven, emission-free technology with high process efficiency (60–80%). However, this process is expensive, as the cost to produce 1 kg of H_2 ranges from USD 7.50 to 10.30 (Campbell 2020).

Table 4. Selected hydrogen production methods and their characteristics

Tabela 4. Wybrane metody produkcji wodoru i ich charakterystyka

Hydrogen production method	Considered raw aterial	Advantages	Disadvantages	Estimated process efficiency [%]	Estimated hydrogen cost (2018) [USD/kg]
Steam reforming	natural gas	developed technology and existing infrastructure	produced CO, CO_2; the volatility of natural gas prices may lead to problems with the supply of the raw material	74–85	1.80–2.27
Partial oxidation	petroleum coke	well-developed technology	along with the production of H_2 – depending on the raw material used – heavy oils and soot may appear	60–75	1.48
Gasification	coal or biomass	available, cheap raw material	fluctuations in H_2 yield due to impurities in the raw material and seasonal availability of biomass; tar formation	30–40	1.63–2.05
Pyrolysis	biomass	available, cheap raw material	tar formation; fluctuations in H_2 capacity due to raw material impurities and seasonal availability	35–50	1.59–1.70
Electrolysis	water	proven technology; zero emissions; existing infrastructure; O_2 as a by-product	storage and transport issues	60–80	7.50–10.30

Efficiency estimates are based on Faraday efficiency, defined as the ratio between the experimentally separated volume of gas (hydrogen or oxygen) and the theoretically calculated volume of gas.

Source: Campbell 2020.

Hydrogen fuel is considered as a promising energy carrier in the coming decades. Table 5 presents the estimated efficiencies of various hydrogen production technologies, both from fossil and non-fossil fuels, such as water electrolysis, biomass, steam reforming, partial oxidation, autothermal reforming, pyrolysis, and plasma technology, as well as their technological maturity level (El-Shafie et al. 2019). However, many of these technologies still face challenges, such as too high total energy consumption and carbon dioxide emissions to the environment.

Reforming and gasification are the most established technologies for hydrogen production. Water electrolysis, when combined with renewable energy, offers an environmentally friendly approach. In addition, it is important to produce hydrogen from a wide range of raw materials. Currently, the maximum production of hydrogen fuel is recorded from steam reforming, gasification, and partial oxidation technologies that rely on fossil fuels.

It has been shown that the efficiency of ammonia decomposition using a catalyst is 28.3%, which surpasses the efficiency of ammonia decomposition without a catalyst (Table 5) (El-Shafie et al. 2019). Research indicates that the production of hydrogen from the decomposition of ammonia is a promising technology, capable of yielding hydrogen with a purity of 99.99%.

Hydrogen technologies still face various challenges that require intensive cooperation between science and industry in order to increase hydrogen production using the developed technologies.

Table 5. Table of efficiency of hydrogen technologies

Tabela 5. Zestawienie efektywności technologii wodorowych

Technology	Raw material	Efficiency [%]	Technological maturity
Steam reforming	hydrocarbons	70–85	commercial
Partial oxidation	hydrocarbons	60–75	commercial
Autothermal reforming	hydrocarbons	60–75	close term
Plasma reforming	hydrocarbons	9–85	long term
Water phase reforming	hydrocarbons	35–55	medium term
Ammonia decomposition	ammonia	28.3	close term
Biomass gasification	biomass	35–50	commercial
Photolysis	sunlight + water	0.5	long term
Dark fermentation	biomass	60–80	long term
Photo fermentation	biomass + sunlight	0.1	long term
Microbial electrolyzes	biomass + electricity	78	long term
Alkaline electrolyzes	H_2O + electricity	50–60	commercial
PEM electrolyzes	H_2O + electricity	55–70	close term
Solid oxide cells	H_2O + electricity + heat	40–60	medium term
Thermochemical splitting of water	H_2O + heat	NA	long term
Photo-electrochemical splitting of water	H_2O + sunlight	12.4	long term

Source: El-Shafie et al. 2019.

Table 6 shows the efficiency and energy demand for different hydrogen production methods (Staffell et al. 2019). Among the different methods of hydrogen production, there are many trade -offs between the scale of production, costs and emissions of greenhouse gases.

Natural gas and hydrogen produced by steam methane reforming are the most cost-effective on a large scale, but this technology has poor environmental performance. If successful in implementing CCS, hydrogen from natural gas would have relatively low emissions and the costs would depend on the available CCS infrastructure. While biomass gasification can also offer large-scale hydrogen production, it comes with higher capital costs.

Although the production of hydrogen from electrolysis is costly, it is more suitable for small -scale generation due to the modular nature of electrolysers. Total greenhouse-gas emissions can be very low if powered by low-carbon electricity (e.g. when combined with offshore wind, so electrolysis stands as a pivotal technology for improving cost profiles.

TABLE 6. Efficiency and energy consumption of hydrogen production pathways

TABELA 6. Efektywność i energochłonność ścieżek produkcji wodoru

Method	Efficiency [%]	Energy demand [kWh/kg H_2]
Methane reforming	72 (65–75)	46 (44–51)
Electrolysis	61 (51–67)	55 (50–65)
Coal gasification	56 (45-65)	59 (51–74)
Biomass gasification	46 (44–48)	72 (69–76)

Source: Staffell et al. 2019.

5. The demand for hydrogen in Poland and Europe – the current state

The global demand for hydrogen in 2020 was ninety million tons. The main global consumers of hydrogen were refineries and the chemical industry. In 2020, refineries used nearly forty million tons of hydrogen, where hydrogen was mainly used in hydro-refining and hydrocracking processes for desulfurization and the production of high-value petroleum products. In the chemical industry, hydrogen has been used as a raw material for many years, mainly for the synthesis of methanol and ammonia. In 2020, approximately forty-five million tons of hydrogen was used to produce ammonia (three-quarters) and methanol (one-quarter). In addition, five million tons of hydrogen was used in the steel industry for the direct reduction of iron ore (DRI). It should be emphasized that the demand for hydrogen in new applications remained at a very low level.

One such example is the fact that less than twenty thousand tons (world) of hydrogen was used in transportation in 2020 (IEA 2021a; IEA 2021b).

The demand for hydrogen in Poland compared to other European Union countries is presented in Table 7. The data stand for the year 2020. In Poland, the greatest demand for hydrogen was observed in the process of ammonia production (386,450 t) and refining (340,293 t). The hydrogen was then used to produce other chemicals (26,535 t). In the energy sector, the annual demand amounted to 10,453 t, while in sectors marked with the “Other” category – 10,162 tons. In total, the demand for hydrogen in Poland amounted to 773,893 tons in 2020.

Polish sources (MC&E 2021) show the demand for hydrogen at the level of about 1 million tons per year, but Poland remains in third place in Europe. This suggests significant potential for further development, which is shown in the Polish hydrogen strategy.

It has to be mentioned (Gawlik and Mokrzycki 2021a) that Poland produces conventional hydrogen almost exclusively. The largest producer of hydrogen is Grupa Azoty, which provides about 42% of this raw material from its four plants: Puławy – 77,000 tons, Kędzierzyn Koźle – 77,000 tons, Tarnów – 73,000 tons. and the chemical plant in Police – 88,000 tons per year (MC&E 2021). In the petrochemical industry, PKN Orlen and LOTOS Group produce the most hydrogen per year, about 200,000 tons (MC&E 2020). Coking plants (Koksownia Przyjaźń, belonging to the Jastrzębska Spółka Węglowa SA Capital Group, and Koksownia Zdzieszowice, owned by Arcelor Mittal Poland SA) have a 12% share in the production of hydrogen as a by-product from coke oven gas (Maj and Szpor 2019).

The developed Polish Hydrogen Strategy defines the goals of the development of the hydrogen economy in Poland, which are to contribute to achieving climate neutrality and keeping the competitiveness of the Polish economy. These goals are as follows:

- the implementation of hydrogen technologies in the energy and heating sectors;
- the use of hydrogen as an alternative fuel in transport;
- support for the decarbonization of industry;
- the production of hydrogen in new installations;
- the efficient and safe transmission, distribution and storage of hydrogen;
- the creation of a stable regulatory environment.

Achieving these goals is primarily associated with a technological change consisting of replacing gray hydrogen with blue, and ultimately, green hydrogen. The implementation of the Polish Hydrogen Strategy objectives would then contribute to accelerating the process of the decarbonization of the most energy-intensive sectors. Its provisions would allow for the ecological production of hydrogen on an industrial scale and the gradual pursuit of a zero-emission economy in Poland. For this purpose, using electricity produced in low- or zero-emission technologies is crucial to achieving the ecological objective of hydrogen produced via electrolysis (Kryzia et. al. 2016; Ceylan and Devrim 2023).

One of the most essential elements of this transformation is the correct definition of the rules for building the hydrogen market, which is currently marginal, as most of the hydrogen produced is used for own needs. Studies on the potential for green hydrogen indicate that Poland could achieve green hydrogen costs comparable to the rest of Europe if more investments

Table 7. Demand for hydrogen in Europe in 2020 [tons/year]

Tabela 7. Zapotrzebowanie na wodór w Europie w 2020 roku [ton/rok]

Country	Refining	Ammonia	Methanol	Other chemicals	Power industry	Transport	Rema-ining	Total
Germany	737,168	414,210	191,715	90,933	77,459	425	232,735	1,744,644
Netherlands	561,882	389,358	84,729	189,577	39,821	144	32,797	1,298,309
Poland	340,293	386,450	0	26,535	10,453	0	10,162	773,893
Spain	420,884	63,933	143	15,435	15,724	1	39,074	555,194
Italy	391,549	77,768	0	26,473	14,649	82	8,505	519,026
Great Britain	270,157	151,648	0	53,783	20,635	0	22,068	518,291
France	236,032	146,377	1,356	23,997	50,529	251	28,357	486,899
Belgium	168,437	166,879	873	54,655	36,715	32	0	427,592
Greece	306,935	21,386	0	0	238	0	11	328,570
Romania	62,826	124,331	30,926	0	4,808	0	90	222,981
Norway	47,444	64,807	92,432	2,202	12,924	113	230	220,151
Hungary	57,895	63,727	12	76,353	5,854	0	1,834	205,676
Lithuania	47,545	149,687	0	0	0	0	0	197,232
Sweden	119,002	0	31,350	8 ,51	10,179	6	1,329	170,616
Slovakia	96,299	63,100	0	1,596	1,937	0	354	163,285
Finland	124,949	0	0	27,467	3,444	0	4,257	160,116
Bulgaria	49,883	83,989	0	0	3,874	0	8	137,754
Austria	50,947	70,639	0	4,728	4,304	5	1,481	132,105
Croatia	55,453	66,058	0	0	0	0	20	121,531
Portugal	89,744	0	0	10,137	6,909	0	0	106,790
Czech Republic	37,869	38,884	0	12,852	4,683	0	8,526	102,814
Denmark	23,919	0	134	0	0	36	530	24,618
Switzerland	11,324	0	0	6,600	0	265	1,953	20,142
Ireland	7,269	0	0	251	0	0	141	7,662
Slovenia	0	0	0	1,608	381	0	66	2,055
Iceland	0	0	794	0	0	3	0	797
Luxembourg	0	0	0	0	0	30	417	447
Latvia	0	0	0	0	0	60	7	67
Cyprus	0	0	0	0	0	0	0	0
Estonia	0	0	0	0	0	0	0	0
Liechtenstein	0	0	0	0	0	0	0	0

Source: FCHO 2023.

are made in renewable energy capacities (Komorowska et al. 2023), including wind and solar technologies.

The ambitions expressed in the hydrogen strategy assume that Poland will become a leader in hydrogen production. However, it should be said that a number of actions in Poland are already overdue because other European countries have very quickly built the legal foundations for the development of hydrogen and have allocated funds for research, development and demonstration projects (Cader et al. 2021). Poland is now entering a crucial phase of market development. If legislative efforts are intensified in the coming months, and conditions for businesses to join the activities of state entities are created, Poland may still secure a significant role on the hydrogen map of Europe. Actions are needed both in the model of centralized top-down management and bottom-up initiatives (EY 2023).

Hydrogen production companies, which are state-owned entities, aim to meet government demand. They intend to expand their production capacity both in the area of market construction and investing in the development of green hydrogen. In October 2021, on the initiative of the Ministry of Climate and Environment, about 140 entities signed the "Sector Agreement for the Development of the Hydrogen Economy in Poland", the purpose of which is to coordinate investments in the development of low-emission hydrogen production technologies and its use.

Only since October 2022 have efforts been underway on the draft amendment to the Energy Law, which introduces solutions that are part of the legislative package called the "constitution for hydrogen". It includes, inter alia, the definition of hydrogen, the rules for licensing activities related to it, as well as issues of storage (including in underground tanks) and transportation via networks.

The key changes provided for in the draft amendment include (SK&S 2023):

- introduction in the Energy Law of a network of terms necessary for the development and functioning of the hydrogen market in Poland, including:

a) extending the catalog of fuels with hydrogen (hydrogen will be a type of fuel next to the solid, liquid, and gaseous fuels previously included in this definition);

b) defining the different types of hydrogen (low-emission, electrolytic and renewable);

c) the introduction of new operators in the scope of hydrogen-related activities – hydrogen system operator, hydrogen combined system operator, and hydrogen storage system operator;

d) defining and regulating new types of activity – storing energy in the form of hydrogen and transmitting hydrogen through hydrogen networks;

e) defining the electrolytic conversion service – the operators that will be required to provide the service to energy companies;

- regulating the rules of hydrogen-related activities, including its licensing;
- defining new types of contracts: provision of hydrogen transmission and storage services and contracts for connection to the hydrogen network;
- authorizing the minister responsible for energy to define, by means of an ordinance, detailed conditions for the functioning of the hydrogen system.

There are also works to establish six hydrogen valleys and increase the sources of research and development.

Summary and conclusions

The Polish Hydrogen Strategy is in line with global, European, and national actions aimed at building a low-emission economy, The document sets Poland up as a potential leader in the hydrogen economy. It should be said that the starting position of Poland at the beginning of the hydrogen revolution is at least favorable. For years, Poland has been Europe's leading producer and consumer of gray hydrogen, used almost exclusively by industry. Replacing it with green hydrogen would be a capital and organizational challenge, but it is a much easier task than building demand "from scratch" in sectors that have not used hydrogen so far.

Considering the development of the hydrogen economy in other European countries, it should be said that those countries have very quickly built the legal foundations for the development of hydrogen and have allocated funds for research, development and demonstration projects.

Poland is now entering a crucial phase of market development. If legislative efforts are intensified in the coming months, and conditions for businesses to join the activities of state entities would be created and Poland may still secure a significant role on the hydrogen map of Europe. It is also very important to intensify the research and development efforts. The anticipated reduction in hydrogen production costs would not occur as quickly as expected without substantial investments in intensive research.

It is also urgent to eliminate barriers hindering the development of renewable energy sources. Without addressing these, it would not be possible to supply large renewable hydrogen production capacities. It is not only about limitations in locating wind-energy capacity but also broadly understood facilitations and preferences in access to the grid and development of RES capacity.

Future research should focus on examining the potential of green hydrogen in Poland in the context of aims defined in the Polish Hydrogen Strategy. There is a need for studies on the potential of green hydrogen produced via electrolysis and its consumption in each sector, including issues related to transportation, storage, and the local context of the current and future hydrogen economy.

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Aleksandra Komorowska, Eugeniusz Mokrzycki, Lidia Gawlik

Produkcja wodoru w Polsce – stan i kierunki rozwoju

Streszczenie

W dobie walki z ociepleniem klimatu i w świetle poszukiwań energii o jak najmniejszym wpływie na środowisko, zainteresowanie wodorem jest naturalnym kierunkiem wykorzystania i rozwoju. Dążąc do zeroemisyjnej Europy do 2050 roku, Unia promuje niskoemisyjny – a docelowo bezemisyjny wodór do jak najszerszego wykorzystania w gospodarce.

Polska opracowała dokument strategiczny określający niezbędne działania wykorzystania wodoru w gospodarce, która powinna jednocześnie utrzymać swą konkurencyjność. Polska jest obecnie trzecim producentem wodoru w Unii Europejskiej, co pozwala na strategiczne myślenie o utrzymaniu w dłuższej perspektywie Polski w roli wiodącego gracza na rynku wodoru. Obecnie wodór w Polsce produkują (zwykle duże) przedsiębiorstwa skarbu państwa (państwowe), na własne potrzeby z niewielkim tylko marginesem jego odsprzedaży. Jest to wodór konwencjonalny (z gazu ziemnego). Trudno zatem mówić o rynku wodoru, a ten musi się rozwinąć, aby można było szeroko wykorzystywać ten surowiec w wielu gałęziach nowoczesnej gospodarki. Wymaga to jednak podjęcia szeregu działań legislacyjnych, badawczo-rozwojowych i inwestycyjnych, a także ukierunkowania transformacji energetycznej kraju na odnawialne źródła energii, które mogą docelowo obniżyć koszty produkcji czystego wodoru.

Podjęto szereg działań, ale opóźnienie w działaniach legislacyjnych spowalnia tworzenie rynku wodoru oraz ogranicza zainteresowanie prywatnego biznesu w angażowanie się w działania transformacyjne.

Słowa kluczowe: Polska, wodór, wydajność produkcji