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Analysis of the Polish Hydrogen Strategy in the Context of the EU's Strategic Documents on Hydrogen

Lidia Gawlik * and Eugeniusz Mokrzycki

Mineral and Energy Economy Research Institute PAS, 31-261 Kraków, Poland; mokrzy@min-pan.krakow.pl
* Correspondence: lidia.gawlik@min-pan.krakow.pl

Abstract: In December 2019, the European Commission unveiled an ambitious project, the European Green Deal, which aims to lead the European Union to climate neutrality by 2050. This is a significant challenge for all EU countries, and especially for Poland. The role of hydrogen in the processes of decarbonization of the economy and transport is being discussed in many countries around the world to find rational solutions to this difficult and complex problem. There is an ongoing discussion about the hydrogen economy, which covers the production of hydrogen, its storage, transport, and conversion to the desired forms of energy, primarily electricity, mechanical energy, and new fuels. The development of the hydrogen economy can significantly support the achievement of climate neutrality. The belief that hydrogen plays an important role in the transformation of the energy sector is widespread. There are many technical and economic challenges, as well as legal and logistical barriers to deal with in the transition process. The development of hydrogen technologies and a global sustainable energy system that uses hydrogen offers a real opportunity to solve the challenges facing the global energy industry: meeting the need for clean fuels, increasing the efficiency of fuel and energy production, and significantly reducing greenhouse gas emissions. The paper provides an in-depth analysis of the Polish Hydrogen Strategy, a document that sets out the directions for the development of hydrogen use (competences and technologies) in the energy, transport, and industrial sectors. This analysis is presented against the background of the European Commission's document 'A Hydrogen Strategy for a Climate-Neutral Europe'. The draft project presented is a good basis for further discussion on the directions of development of the Polish economy. The Polish Hydrogen Strategy, although it was created later than the EU document, does not fully follow its guidelines. The directions for further work on the hydrogen strategy are indicated so that its final version can become a driving force for the development of the country's economy.

Keywords: hydrogen; green hydrogen; hydrogen economy; hydrogen strategy; European Green Deal; Poland

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1. Introduction

In the last few years, there has been a significant increase in the interest in hydrogen as an energy carrier. The development of hydrogen technologies and the hydrogen economy will make it possible to solve the three main challenges facing the global energy sector [1–3]: the need to meet the growing demand for clean gaseous and liquid fuels and electricity; the need to increase the efficiency of fuel and energy production; and reducing the emission of harmful substances into the atmosphere, including greenhouse gas emissions.

Hydrogen is a versatile chemical element that can be obtained from many sources using several methods, starting from hydrocarbon steam reforming through electrolysis and pyrolysis and ending with bacterial fermentation. Thanks to its current wide use in the chemical, refining, and steel industries, hydrogen remains a strategic raw material for many sectors of the economy.

It is traditionally used as a raw material, process gas, or fuel in liquid or gaseous form in several industries. It is mainly used in industrial processes, including the production of ammonia for fertilizers (50%), in refineries (35%), and in the food, electronics, and glass and metal industries. In the petrochemical industry, it is used for hydrotreatment, hydrocracking, and reforming. The chemical industry uses hydrogen, inter alia, to produce ammonia, produce margarine by hydrogenating the unsaturated fats in vegetable oils, reduce iron ores, and to produce hydrogen chloride by combining chlorine and hydrogen [4]. In the food industry, it is used as a food additive (E949), as it protects packaged goods against oxidation. It is also used in burners for cutting, soldering, and welding metals as well as fuel in hydrogen cells, internal combustion engines, and jet engines. It was originally used to fill balloons and airships. It can also be used as a cooling medium, for example, in turbo generators in power plants.

However, hydrogen is highly flammable, reactive, and explosive when mixed with oxygen. The use of hydrogen, especially as a fuel, is associated with the maintenance of appropriate safety technologies and professional devices, which was not conducive to the rapid development of hydrogen technologies.

In recent decades, the increased interest in hydrogen has been driven by the fact that hydrogen provides the cleanest energy and most efficient combustion. Another reason is the drive to develop technologies that reduce carbon dioxide emissions, which many countries committed to at the 1997 Kyoto conference. The main goal is to limit the increase in the global average temperature to below 2 degrees Celsius, preferably 1.5 degrees Celsius, compared to preindustrial levels [5].

Hydrogen can produce electricity and electricity can produce hydrogen, thus creating an energy loop that is renewable and harmless to the environment.

Hydrogen, thanks to its natural physicochemical properties, is an excellent fuel. Compared to other fuels, hydrogen has the highest lower heating value (per unit mass) 120 MJ/kg and higher heating value 141.9 MJ/kg [6]. Due to its very low density, hydrogen compares poorly with other fuels, when these values are related to the volume. As a conventional fuel, it is mainly used in rocket engines.

In motor vehicles, hydrogen can be used as a fuel to power internal combustion engines where it produces significantly lower emissions of toxic exhaust gases than other fuels. However, since hydrogen is a hazardous gas, due to its wide flammability range (mixed with air) and a very low ignition energy, the dominant development direction is the generation of electricity in fuel cells.

The potential of hydrogen has been noticed and technological development in the areas of production and use of this raw material has become the driving force behind the development of low- and zero-carbon economies. However, this applies only to some technologies of its production, as the hydrogen type determines its emission levels and competitiveness, considering the entire production chain.

The following types can be determined:

- Renewable hydrogen (green hydrogen) produced through the electrolysis of water using electricity from RES;
- Low-carbon hydrogen (blue hydrogen), hydrogen produced from nonrenewable or renewable energy sources with a low carbon footprint;
- Conventional hydrogen (grey hydrogen) produced by various processes (natural gas steam reforming, coal gasification, or separation from coke oven gas) using fossil fuels.

This classification is based on the emissions of the production process. Green hydrogen generation technologies also include biogas reforming or biochemical biomass conversion, if sustainability requirements are met. Electrolytic hydrogen, i.e., hydrogen produced by electrolysis of water can be classified into all three of the above groups, depending on the carbon footprint of the electricity production. The well-to-gate greenhouse gas emissions in the EU electricity mix are 14 kg CO_{2eq}/kgH_2, compared with 26 kg CO_{2eq}/kgH_2 for the global average electricity mix [7]. This hydrogen should be classified as conventional hydrogen. In the case of renewable hydrogen produced from electricity from renewable sources, these emissions are close to zero [7]. The use of carbon capture technology to produce hydrogen from fossil fuels combined with the use of an electrolysis process and a significant reduction in greenhouse gas emissions over the entire life cycle compared to current hydrogen production leads to the production of blue hydrogen.

Renewable hydrogen will play an important role in the energy transformation of global economies [8]. Currently, new technologies for the production of hydrogen, including those using renewable energy, are not cost-competitive, although largely nonpolluting [9].

In the European Union, clean hydrogen technologies are one of the key elements of the energy transition announced in the European Green Deal [10].

The European Commission Communication on a Hydrogen Strategy for a Climate Neutral Europe [11] provides a vision of how the EU can use hydrogen to gradually decarbonize different sectors of the economy. The idea is based on the assumption that technology development will lead to increasingly low-carbon hydrogen production, while lowering production costs, which are currently not competitive for low-carbon and renewable hydrogen.

In the EU, the estimated cost of hydrogen from fossil fuels is around EUR 1.5 /kg and depends mainly on the price of natural gas. The price of hydrogen produced from fossil fuels with CCS is around EUR 2/kg, while it is EUR 2.5–5.5/kg for renewable hydrogen [7]. Carbon prices in the range of EUR 55–90 per ton CO_2 would be needed for hydrogen produced from fossil fuels with CCS to make the hydrogen from renewable fuels competitive. The energy policy of the EU countries will support the implementation of hydrogen in energy systems, and R&D will contribute to the reduction in costs and improve its competitiveness [12].

At the beginning of 2021, public consultations of the draft Polish Hydrogen Strategy were held in Poland [13]. The project covers the directions of development of national competences and technologies for the use of low-carbon hydrogen in three sectors: energy, transport, and industry, as well as its production, distribution, and the necessary legal changes and financing.

The purpose of this article is to thoroughly analyze this document and show the important similarities and differences with the European Commission's 'Hydrogen Strategy for a Climate-Neutral Europe' published in 2020. The analysis focuses on assessing whether the presented strategy is in line with the direction set out in the EU documents, indicates the issues where the Polish government's approach is different and what their consequences may be. The compliance of the presented strategy with other already in force in the government's and EU's documents was also assessed, and the main work that should be undertaken so that the final document can be implemented quickly and efficiently is indicated. As the final document is still in the preparation process in the government, this evaluation may contribute to the facts in order for the final document to avoid the weaknesses that may lead to the failure to achieve the EU's decarbonization goals by 2050.

The article covers: an analysis of the current situation of hydrogen production and consumption in Poland against the background of the European Union, a discussion of the objectives outlined in the Polish Hydrogen Strategy, presentation and discussion of the results of the analysis as well as arguments for changes to the final version of the strategy.

2. Materials and Methods

The research used the method of critical text analysis. The subject of the analysis is the draft Polish Hydrogen Strategy [13]. This document was examined and assessed in terms of its compliance with the assumed long-term goals of the European Union presented in the New Green Deal [10] and in the strategic document 'Hydrogen Strategy for a Climate-Neutral Europe' [11]. The result of this analysis is the authors' assessment of compliance or noncompliance with these documents, together with an assessment of how the adopted solutions may affect the pace and effectiveness of implementation. The data presented in the draft document were also verified in terms of their reliability with the existing state of the hydrogen industry in Poland. The correctness of the assumed plans was checked with the possibilities of their implementation by assessing the consistency with the currently binding government documents, mainly in the field of energy policy, as well as with the study: National Plan for Energy and Climate for 2021–2030 [14] submitted to the European Commission for evaluation.

3. Discussion

3.1. Hydrogen Demand and Production in Europe and Poland

Hydrogen consumption in Europe was around 8.3 million tons in 2018 [15], of which 3.7 million tons, or 45%, was consumed by refineries. A further 2.8 million tons (34%) was used for the production of ammonia. Together, these two sectors accounted for almost 4/5 of the total hydrogen consumption in the EEA (European Economic Area). About 12% was consumed by the chemical industry to produce methanol (about 5%) and other chemical products (7%). Hydrogen is also used in small amounts (around 1%) in the energy sector to cool generators or (as a byproduct) to generate electricity and heat.

Other uses of hydrogen, such as in transport, the glass industry, the metallurgy and steel industries, and the food industry have a small share in the total consumption.

More than half of the total hydrogen consumption in Europe takes place in just four countries: Germany (22%), the Netherlands (14%), Poland (9%), and Belgium (7%) [15].

Currently, about 120 Mt of hydrogen is produced worldwide each year, of which two-thirds is pure hydrogen and one-third is a mixture with other gases [16]. Estimates show that the total hydrogen production capacity in Europe is about 11.5 million tons per year, 65% of which are hydrogen generating units that produce hydrogen on-site for self-consumption (captive production), usually refineries and ammonia and other chemical plants. Around 20% of total production capacity is hydrogen produced as a byproduct of coal coking processes; small quantities are also produced during the production of chlorine compounds, ethylene, and styrene. The byproduct produced in coking plants is a mixture of hydrogen and coke oven gas. Such a product can be used in a limited way, usually in the metallurgical and steel industry as an enrichment additive for other process gases.

The hydrogen market is small. Merchant hydrogen production plants represent only 15% of total hydrogen production capacity. The structure of production by type and technology across countries is similar, while captive production is the largest production segment in most countries.

Hydrogen is predominantly produced by reforming fossil fuels (mainly natural gas) [1,2]. The production capacity of pure hydrogen is small, with blue hydrogen production capacity less than 1% and green hydrogen production capacity less than 0.1% [17].

In Poland, production for self-use is greater than in other countries and the amount of hydrogen produced for commercial use is small. Most of the hydrogen traded on the Polish market comes either from excess capacity in the production of hydrogen in chemical plants and refineries or is a waste product [13].

Poland is one of the major hydrogen producers in Europe. In 2015, the total production was estimated at one million tons. The largest producer of hydrogen is Grupa Azoty (nitrogen plants in Puławy: 190 thousand tons per year, Kędzierzyn Koźle: approx. 77 thousand tons per year, hydrogen plant in Tarnów: 73 thousand tons per year, and the chemical plant in Police: 88 thousand tons per year). About 42% of the raw material in Poland is produced in these plants.

At Grupa Azoty, the range of merchant hydrogen offered to external partners is growing each year currently around 600 tons per year. Grupa Azoty Puławy and Grupa Azoty Kędzierzyn, both of which have plans to expand their production capacity, sell hydrogen. Because of the use of hydrogen in the food industry, Grupa Azoty Puławy is FSSC 22 000 certified. Grupa Azoty is also working on the development of fuel cells [18] and is considering joining the national strategy for the development of hydrogen transport [19].

In the petrochemical industry, PKN Orlen and LOTOS Group produce the most hydrogen per year, about 145 thousand tons each [20].

These players, too, are actively thinking about investing in clean hydrogen production. For example, the LOTOS Group S.A. [21] wants to become one of the ten largest green energy producers in Europe within six years thanks to the implementation of the Green

H_2 project, under which by the end of 2025 an electrolyzer park with a capacity of up to 100 MW is to be built in the Gdańsk refinery.

Coking plants (Koksownia Przyjaźń, belonging to the Jastrzębska Spółka Węglowa SA Capital Group, and Koksownia Zdzieszowice, owned by Arcelor Mittal Poland SA) have a significant share in the production of waste hydrogen [22]. Hydrogen is also produced for self-use by companies in the fat industry and used, for example, when hardening vegetable oil.

Currently, Poland produces almost conventional hydrogen exclusively. This is due to the constant industrial demand. The production of such hydrogen from natural gas generates CO_2 emissions of over 5.8 kg/kg H_2 and in the case of hard coal, over 10 kg CO_2/kg H_2 [7].

The mechanism of the EU Emissions Trading System (ETS), which gradually increases the cost of allowances, provides a market-based incentive for a gradual shift from fossil-based hydrogen to other forms of its production.

Low-carbon hydrogen is the hydrogen produced from nonrenewable or renewable energy sources with a low carbon footprint.

Fuel prices and the cost of CO_2 capture and storage influence the price of low-carbon hydrogen produced from fossil fuels. The cost-optimal solution is to use hydrogen produced as a byproduct of chemical processes (so-called waste hydrogen).

Renewable hydrogen is produced through the electrolysis of water using electricity from RES. During its production, CO_2 emissions remain below 1 kg CO_2/kg H_2. An additional advantage of this technology is the possibility obtaining of high purity gas (at least 99.999%, the so-called hydrogen 5.0). Renewable hydrogen can be obtained from P2G (Power to Gas) facilities, where excess electricity from RES is used to generate hydrogen.

The use of renewable energy sources for the production of hydrogen in Poland is currently limited due to the lack of appropriate installations and the low level of commercialization of existing technologies. There are also no system solutions for the management of excess electricity from renewable energy sources through the production of hydrogen by electrolysis at times of reduced electricity demand.

Hydrogen as a product of electrolysis can be used in various ways. Using fuel cells, hydrogen can be converted back into electricity. Compressed hydrogen can be stored and used as a fuel. It can be a raw material for chemical syntheses. By reacting with carbon dioxide, hydrogen can be converted into synthetic methane and be distributed through gas networks. In certain quantities, depending on the infrastructure used and the target applications, pure hydrogen can be blended with conventional gas fuel.

Poland's government plans to develop hydrogen production as well as other segments of the hydrogen economy, i.e., transmission and distribution, storage, and use of hydrogen in industry. Hydrogen technologies are developing in many countries, including Poland, although only in recent years there have been projects aimed at using this type of technology to decarbonize the economy. The main players in this area are large fuel and energy companies and the State Treasury [23].

3.2. External Conditions for the Use of Hydrogen for a Climate-Neutral Economy

The IEA's call for widespread use of hydrogen has been included in hydrogen strategies announced by several countries around the world, which vary in scope, scale, and implementation period [24].

The European Commission's hydrogen strategy ('A hydrogen strategy for a climate-neutral Europe') [11] presents hydrogen as a raw material and fuel capable of decarbonizing the economy in various areas. This vision can be realized by the installation of at least 6 GW of electrolyzers powered by renewable energy by 2024, producing up to one million tons per year of green hydrogen, and 40 GW of hydrogen electrolyzers, capable of producing up to ten million tons of renewable hydrogen by 2030.

According to the European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy [25] the share of hydrogen in Europe's energy mix is projected to increase from less than 2% [26] today to 13–14% by 2050 [27].

Total investments in renewable hydrogen in Europe could reach EUR 180–470 billion by 2050, and investments in low-carbon hydrogen from fossil fuels EUR 3–18 billion [24].

The development of a hydrogen value chain in the EU, for a wide range of industrial sectors and other end-uses, could directly or indirectly provide jobs for up to one million people [26]. Analysts estimate that clean hydrogen could meet 24% of energy world demand by 2050, with annual sales in the range of € 630 billion [28].

The hydrogen ecosystem in Europe will probably develop gradually at different paces in different sectors and regions. The EU's priority is to develop renewable hydrogen production using mainly wind and solar energy. This will require various political solutions.

In contrast, the European Commission's communication on energy system integration [29] sets out a vision of accelerating the transition to a more integrated energy system that supports a climate-neutral economy at the lowest cost per sector. Energy system integration refers to the planning and operation of the energy system as a whole, considering individual energy carriers, infrastructures, and energy consumption sectors. It includes three complementary and mutually supportive tasks:

- a more circular energy system, the key element of which is energy efficiency and where priority is given to the least energy-consuming solutions;
- more widespread direct electrification of end-use sectors;
- the use of renewable and low-carbon fuels, including hydrogen, for end-uses.

Electricity demand is projected to increase significantly in final energy consumption from the current level of 23 to around 30% in 2030 and to 50% by 2050. This growing demand for electricity will rely heavily on renewable energy. By 2030, the share of energy from renewable sources should increase to 55–60%, and to around 84% by 2050.

3.3. Poland's Activities in the Field of Hydrogen Use

Poland is committed to global climate efforts through a broad discussion on the future shape of the hydrogen market at the EU forum.

The Strategy for Responsible Development until 2020 (with a perspective until 2030) [30] should be mentioned here; its main objective is to create conditions for the growth of income of Polish inhabitants, while ensuring the growth of cohesion in the social, economic, environmental, and territorial dimensions. The ruling coalition's recently announced new document 'The Polish Deal' [31] is a post-pandemic recovery plan based on state support for likely voters and significant tax changes for businesses. Among the issues to be implemented, there is also the topic of clean energy, clean air, which consists of over a dozen projects, including the development of hydrogen technologies, where we read about the adoption of the 'strategy covering the development of the full hydrogen economy value chain from electrolyzers that convert energy into hydrogen, through cells and storage technologies, to using hydrogen in energy production and greening the transport, heating, or metallurgy sectors' [31].

The hydrogen strategy is part of the strategic projects foreseen in the Strategy for Responsible Development: Flagship Project: Electromobility, Strategic Projects: Electromobility Development Program, Polish Nuclear Power Program. The Energy Policy of Poland until 2040 (PEP2040) [32] adopted this year, sets the directions for the development of the energy sector, considering the tasks necessary to be implemented in the short term, including hydrogen.

The shape and implementation of the Polish Hydrogen Strategy [13] is conditioned by several obligations resulting from Poland's participation in international institutions and the strategic documents. These include:

- The 1992 UNFCCC convention [33];
- The 1977 Kyoto Protocol [34];

- The Paris Agreement in force since 2016 [35]; its key objective is to limit the increase in global average temperature to below 2 °C above preindustrial levels and to make efforts to limit the temperature increase to 1.5 °C.
- UNIDO report on the importance of hydrogen technologies in the decarbonization of industry and energy [36].

In the case of the EU, the long-term goal is to achieve climate neutrality by 2050, in line with the European Commission's vision presented in 2018 at COP-24 in Katowice [25] and confirmed in the European Commission's Green Deal [10].

The Polish Hydrogen Strategy is part of the government's action plan for a just energy transition, which will build a zero-carbon energy system and improve air quality. The implementation of the strategy will also support the development of RES.

The draft Polish Hydrogen Strategy presents the terminology and classification of hydrogen types depending on the emissions from the production process. This is a different approach from the European Commission's proposal, where the priority is to use green hydrogen. On the other hand, the EU strategy accepts a transitional (until the economic viability of green hydrogen is achieved) use of low-carbon hydrogen.

The Polish Hydrogen Strategy proposes two main categories of hydrogen:

- Conventional hydrogen, produced by different fossil fuel processes, primarily natural gas steam reforming, coal gasification, or coke oven gas separation, with emissions above 5.8 kg CO_{2eq} per kg H_2. The Polish strategy focuses on the use of natural gas rather than coal, as emissions from the production of hydrogen from coal are significantly higher. The main advantage of this type of hydrogen is its price, as it is the cheapest production method;
- Low-carbon hydrogen produced from nonrenewable or renewable energy sources with a low carbon footprint. According to the Polish strategy, the production of low-carbon hydrogen emits up to 5.8 kg of CO_2 equivalent per kg H_2. Various technologies can be used to produce this type of hydrogen, including steam reforming of hydrocarbons with CO_2 capture and storage (CCS) or CO_2 capture and use (CCU), coal gasification with CCS or CCU, biomass gasification with CCS or CCU, electrolysis using electricity from renewable energy sources, electrolysis using electricity from conventional sources with CCS or CCU, pyrolysis, and chemical processes that produce hydrogen as a byproduct, including separation of hydrogen from coke oven gas. The costs of these technologies are influenced by several factors, mainly the price of gas and the costs of using CCS, which are still relatively high.

It should be noted here that hydrogen generated as a byproduct of chemical processes (the so-called waste hydrogen) is classified as low-carbon one, because the resulting emissions are due to other processes.

The key messages of the strategy are as follows:

- Hydrogen is a chemical element with versatile properties that can be extracted by various processes, from steam reforming of hydrocarbons to electrolysis or bacterial fermentation; it is used in the chemical industry (main direction of consumption), refining, metallurgy, transport, or energy industries;
- The ambition of the Government of the Republic of Poland is to develop strong national and local competences in the production of key components of the hydrogen technology value chain; it is necessary to develop electrolyzer and fuel cell installations, distribution networks, hydrogen storage facilities, and refueling infrastructure;
- Hydrogen will be one of the key fuels in the energy transition taking place in the European Union;
- The development of the hydrogen economy is both an opportunity and a challenge;
- Hydrogen technologies are and will be supported in Poland and the EU.

There are six main objectives to be achieved by 2030. Specific actions to be taken in the short term (up to 2025) and medium term (up to 2030) to achieve these objectives have been identified.

They include:

1. Implementation of hydrogen technologies in the energy sector
2. Use of hydrogen as an alternative fuel in transport
3. Support for industry decarbonization
4. Hydrogen production in new installations;
5. Efficient and safe hydrogen transport;
6. Creation of a stable regulatory environment.

Within these six objectives included in the draft Polish Hydrogen Strategy, 23 actions are to be implemented by 2025 and 17 actions by 2030.

The use of hydrogen technologies in the power industry (Table 1) is a logical solution due to the increase in the share of non-controlled electricity from RES in Poland's energy mix, up to about 32% in 2030 [32]. This makes it necessary to ensure energy balancing in periods when RES are not supplying electricity to the grid. The use of electrolysis is one of the solutions for increasing system flexibility and efficient use of power plant capacity maintained to ensure continuity of supply, including planned nuclear power plants.

Table 1. Actions envisaged in the Polish Hydrogen Strategy as part of the implementation of Objective—1 Implementation of hydrogen technologies in the energy sector.

By 2025	By 2030
1. Implementation of the legal framework for hydrogen technologies in the energy sector	6. Co- and poly-generation installations with a capacity of 50 MW_t (combined heat and power plants, approx. 590 GWh H_2/year)
2. P2G installation with a capacity of 1 MW (3150 MWh H_2/ year)	7. The use of stored hydrogen (approximately 4700 MWh) for electricity generation (approximately 11 GWh/year)
3. Co-combustion of hydrogen in gas turbines (where technologically possible)	8. The development of co- and poly-generation systems with a power of 10–250 kW using fuel cells (block of flats, small housing estates, public utility facilities)
4. R&D support for the development of co- and poly-generation systems with a power of 10–250 kW using fuel cells (block of flats, small housing estates, public utility facilities)	
5. Technical feasibility study on the use of salt caverns for hydrogen storage	

The tasks set in the field of hydrogen use in transport (Table 2) are extremely ambitious, fully in line with the directions set by the European Commission. The plan to investigate the possibilities and profitability of using hydrogen in the transport of synthetic gases generated in the process of hydrogen methanation deserves special attention. By 2030, it is planned to produce synthetic fuels in the reaction of hydrogen with CO, CO_2, and N_2, thus preparing the ground for their future use in subsequent transport segments.

Table 2. Actions envisaged for in the Polish Hydrogen Strategy as part of the implementation of Objective 2—Use of hydrogen as an alternative fuel in transport.

By 2025	By 2030
9. Use of 500 new hydrogen buses manufactured in Poland (demand for 3232 Mg H_2, i.e., approximately 108 GWh H_2/year)	15. Further development of H_2 refueling infrastructure
10. Development of hydrogen refueling network: 32 stations	16. Use of 2000 hydrogen buses made in Poland
11. Construction of hydrogen purification plants (up to 99.999 purity)	17. Further development of H_2 purification plants (up to 99.999 purity)
12. Hydrogen-powered locomotives for routes that are difficult to electrify	18. Successive replacement of diesel trains with hydrogen-powered trains
13. Investigation of the possibility of using synthetic gases, obtained in the H_2 methanation process, in transport	19. Further extensive use of H_2 in heavy transport (demand for about 32,462 Mg H_2, i.e., 1081 GWh H_2/year—approximately 3% of current production from primary fuels)
14. Pilot programs for the use of H_2 in heavy transport (road, rail, sea, and river transport)	20. Production of synthetic fuels by the reaction of hydrogen with CO, and CO_2, N_2 (with a demand of about 237 GWh H_2/year)

The use of hydrogen in the chemical, refining, and steel industries (Table 3) makes it a strategic raw material for the Polish economy. To maintain the strong position of Polish industry in the EU, it is necessary not only to ensure price competitiveness, but also innovation and transformation towards a low-carbon and ultimately climate-neutral model.

Table 3. Actions envisaged in the Polish Hydrogen Strategy within the implementation of Objective 3—Supporting industrial decarbonization.

Until 2025	Until 2030
21. The use of low-carbon hydrogen in petrochemical, chemical, and fertilizer production processes 22. Introduction of the 'Carbon Contracts for Difference' as an instrument to support the climate transformation of industry 23. Pilot technology projects for sectors where climate neutrality is difficult to achieve (primarily steelmaking) 24. Financial support for feasibility studies of hydrogen valleys as part of the construction of closed-loop industrial processes.	25. Development of at least 5 hydrogen valleys with H_2 transmission infrastructure (pipelines)

The implementation of a support system in the form of a 'Carbon Contract for Difference' will increase the interest in the use of green hydrogen in the industry. However, the Strategy does not elaborate on this issue: there is no definition of this support system, scope of application, and there are no regulatory policies [37].

The ambitious plan to build hydrogen valleys with the necessary infrastructure is especially worth noting. Unfortunately, apart from a vague listing of actions, the Strategy does not provide details of these.

It is estimated that mass-scale implementation of distributed P2G, P2L, P2X systems (Table 4) based on 1 MW class high-temperature electrolyzers in the Polish economy is possible within 5 years. For 10–50 MW class installations, this horizon extends to 7–10 years. Currently, there are no manufacturing plants in Poland that carry out industrial production of solid oxide electrolyzers and components for systems with these electrolyzers. However, there are solutions at various stages of development that require further R&D and commercialization.

Table 4. Actions envisaged in the Polish Hydrogen Strategy within the implementation of Objective 4—Hydrogen production in new installations.

By 2025	By 2030
26. Installation with a minimum capacity of 50 MW for the production of hydrogen: in the electrolysis process from biomethane, from waste gases, natural gas, and by pyrolysis	28. Utilization of the installed 2 GWh electrolyzers for the production of H_2 (production of approximately 6415 GWh H_2 per year, i.e., 193 643 Mg H_2/year
27. Synthetic gas production from hydrogen in a methanation process, the use of low-carbon H_2 in the production of NH_3	
	29. Ensuring conditions for the construction of a H_2 production facility at a nuclear power plant

By 2030, the strategy plans to launch 2 GW of electrolyzers. This is a realistic goal from a technical point of view. It is also fully consistent with the direction indicated by the EU. However, the production of hydrogen in these new installations would be around 200,000 tons per year and about 9.5 TWh of electricity is needed [24]. The production of low-carbon hydrogen requires this amount of electricity from renewable energy sources.

Meanwhile, in the document Energy Policy of Poland until 2040 [32], the gross electricity production balance indicates that the production volume required to meet the demand is 201.2 TWh, of which 64.2 TWh is from all renewable sources. Cheap sources of energy that could be used to produce hydrogen are wind energy and photovoltaics in periods when production from these sources is excess in relation to the demand. The forecast shows that in 2030 these sources will produce 42.2 TWh of energy for the power system. Obtaining an additional 9.5 TWh of excess energy from them, which could be used in electrolyzers, i.e., an additional 22.5%, is not realistic.

Therefore, the adoption of the hydrogen strategy in this form leads to the need to verify the already approved documents in the field of energy policy. Otherwise, the electricity for the electrolyzers will be imported or produced from conventional sources (coal or gas based), which runs counter to the EU's goal of moving towards a zero-carbon economy.

In the near future, the most optimal form of energy transmission (Table 5) for the development of the hydrogen economy is to be worked out, including the transmission of electricity to the place of hydrogen production, hydrogen transmission, SNG transmission with the existing gas network, or hydrogen transmission through dedicated pipelines. In the longer term, it is planned to adapt selected sections of the gas network to transmit and distribute hydrogen mixed with gas (up to 10%) while SNG produced in P2G plants is to be introduced into the gas network. However, there are serious doubts as to whether the current technical condition of the gas network in Poland will allow natural gas to be mixed with hydrogen on a larger scale [22].

Table 5. Actions envisaged in the Polish Hydrogen Strategy within the implementation of Objective 5—Efficient and safe transmission of hydrogen.

Until 2025	Until 2030
30. Grid development and hydrogen distribution analysis for the development of hydrogen economy: electricity transmission/transmission of H_2/SNG with the existing gas network/pipeline transmission of hydrogen	33. Adaptation of selected sections of the gas network for the transmission and distribution of H2 doped with gas
31. Feasibility study for the North–South pipeline (hydrogen highway)	34. Construction of pipelines for the transmission and distribution of H_2 or extension of the power grid to transmit electricity
32. Research attempts to use the existing gas infrastructure for the injection of H_2 and transmission of H_2 mixtures with gas	35. Introduction of SNG produced in P2G plants into the gas network

Attention should be drawn to the deadlines set in the draft Polish Hydrogen Strategy in the area of establishing a legal basis for the hydrogen market (Table 6). The assumed fast pace of action is not kept. In the second half of 2021, the final version of the Polish Hydrogen Strategy has not yet been prepared, not to mention the implementation of the set goals. The pace of action regarding the resolution of legal issues related to the conditions for the functioning of the hydrogen market and the technical conditions of its transmission and safe use indicate that delays are to be expected at the outset.

Table 6. Actions envisaged in the Polish Hydrogen Strategy within the implementation of Objective 6—Creation of a stable regulatory environment.

Until 2025	Until 2030
36. Creation of a regulatory framework for the functioning of H_2 as an alternative fuel in transport (Q1 2021) 37. Laying the foundations for the H_2 market (Q3–Q4 2021) 38. Development of the hydrogen legislative framework on the functioning of the market, implementing EU law	

The Polish Hydrogen Strategy states that it is necessary to introduce legislation that will enable the operation of the hydrogen market without detailed regulations. It is proposed to introduce a definition of hydrogen in the Energy Law Act [38], as it is not clear at present whether hydrogen can be treated in the same way as natural gas. In addition, it was proposed that activities in this market should not be subject to licensing and, thirdly, as part of establishing the rules for the functioning of the hydrogen market, it was recommended not to implement ownership unbundling rules. It can therefore be concluded that the Polish government is aiming for the hydrogen market, at least in the initial phase of development, not to be a regulated market at all or to be regulated only to a minimal extent.

The European hydrogen strategy points to the need for clear rules at an early stage of market development to avoid investments that could generate losses or require intervention costs if later regulations ruled them out. The Commission has announced that it will revise EU gas rules in 2021 to meet the needs of competitive decarbonized gas markets [11]. It is not yet determined what regulatory framework the Commission wants to design for the hydrogen market, but it seems that it will be based on the regulation of natural gas, so it would be a regulated market. It therefore seems necessary to wait for EU guidance in this area.

In addition to the 38 basic actions defined under the objectives of the Polish Hydrogen Strategy, two horizontal measures are planned, namely:

- Action 39: Use of the Polish research and development potential in the field of hydrogen technologies,
- Action 40: Achieving the status of a supplier of electrolyzers, pyrolysis installations, fuel cells and hydrogen tanks, reactors and catalysts for methanation (P2G), or P2L technology and other components (including pipelines, valves, seals, compressors, pumps, security automation).

It seems that these activities are crucial for the achievement of all the previously mentioned goals. However, little attention has been paid to determining how much this would all cost and where the investment funds would come from. It is planned to create multiyear programs and support programs for the development of hydrogen technology through Polish funds, EU funds, the National Center for Research and Development funds, and the National Fund for Environmental Protection and Water Management funds. However, apart from some purchase investments, the costs of implementing the strategy are not specified, and the announced support programs are insufficient.

3.4. Results—Evaluation of the Draft Polish Hydrogen Strategy

The draft Polish Hydrogen Strategy is the response of the Polish government to the 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'. It is based on similar substantive and technological solutions.

The structure of the draft hydrogen strategy presented by the government is generally correct. The presented development goals focus on the three most important sectors in which hydrogen can be used, i.e., energy, transport, and industry. The plans are very ambitious and include issues related to the production and use of hydrogen and investments in infrastructure and the development of research on hydrogen technologies.

Poland has good foundations for the development of the hydrogen economy, as it is currently one of the largest European producers of this raw material, mainly for the needs of the refining and fertilizer industries. Participation in hydrogen consumption (9%) puts it in third place among the largest consumers of hydrogen in Europe. It should be emphasized, however, that the experience in the production mainly concerns grey hydrogen produced from natural gas and a certain amount of waste hydrogen resulting from the processes of coking coal, i.e., high-emission hydrogen.

It is important that the project defines in detail and realistically the uses of hydrogen in the economy, where there are the greatest opportunities for development: in transport, industry, power generation, and heating. It indicates specific directions of development of technologies using hydrogen: buses, polygeneration systems (parallel generation of electricity and heat), in buildings, energy storage, and for the needs of the power system.

However, quantitative targets for hydrogen use in the medium (2030) and long term (2040 and 2050) are missing; thus, the document cannot be regarded as a long-term determinant for the development of this market. A detailed document on the long-term potential of hydrogen technologies should therefore be developed.

It has to be stated that the planned time horizon is too short. In fact, this is a shortcoming of all the strategic documents presented by the government: The hydrogen strategy is not reflected in other important documents that set the direction for the development of the energy sector the recently adopted Polish Energy Policy [32] and the National Plan for Energy and Climate [14]. As such, it is impossible to judge how close the zero-emission target Poland would be in 2050.

4. Summary and Conclusions

The country's experience and position in hydrogen production provides a good basis for further development. In the long term, it is aimed at building Poland's energy independence (green hydrogen), but in the perspective covered by the analysis, it promotes the production of hydrogen from natural gas, which is usually imported. The replacement of domestic coal with natural gas significantly reduces the carbon intensity of the process, but increases the need for imported gas, which is subject to significant price fluctuations, not helping to stabilize the price of the hydrogen produced.

The draft strategy mentions that a 'Potential analysis of hydrogen technologies up to 2030 with an outlook to 2040' is being elaborated, the results of which will be included in the final version of the strategy. However, the assumptions and results of the analysis should be subject to public discussion before being approved.

The recently adopted Polish Energy Policy [32] and the National Energy and Climate Plan [14] need to be updated to be consistent with the final version of the Polish Hydrogen Strategy. The detailed analysis shows that the RES development goals proposed are insufficient to ensure the development of green hydrogen. The inconsistency of the documents is particularly evident at the level of projected demand for electricity, including from renewable sources. Meanwhile, the current restrictions on the location of wind farms [39] are slowing down the development of onshore wind energy. Announced less favorable conditions for photovoltaic prosumers regarding cooperation with the grid and distribution companies [40] may slow down the growth rate of installation of photovoltaics on residential buildings. Although the draft hydrogen strategy assumes, among other things, the use of electricity from nuclear power plants to produce green hydrogen (which also differentiates the Polish hydrogen strategy from the directions indicated in the EC strategy), it is known that the first nuclear power unit may not be built until 2033, not to mention the probable delays of the nuclear energy project.

It will be necessary to revise the National Energy and Climate Plan [14] towards increased electrification of the country's economy (higher energy consumption) with a simultaneous higher share of generation from renewable energy sources. This direction will additionally support the perception of Poland as a country joining the global climate crisis. It will also help to favor the perception of the country by the European Commission, which assessed the current National Energy and Climate Plan as unambitious.

The Polish strategy points to legislative shortcomings in the hydrogen market and announces a comprehensive legal act in the form of the Hydrogen Law. It should be noted that the EU is working in parallel on regulating the hydrogen market. It would be highly desirable for the Polish Government to cooperate with the Union in this area to avoid contradictory legislation.

Although the draft of the Polish hydrogen strategy is not a comprehensive document and the directions of changes are outlined only in slogans, especially in the area of the proposed solutions for the hydrogen market, the direction indicated by the Polish government is not consistent with the proposal of the European Commission presented in the 'Hydrogen strategy for a climate-neutral Europe'.

Summing Up

The draft presented is a good basis for further discussion on the directions of development of the Polish economy. A good start is to set a realistic quantitative target of installing 2 GW of electrolyzers. This supports Poland's decarbonization goals.

The main directions for the use of hydrogen are set out in a clear and realistic way. Research and development directions are outlined, recognizing the key importance of efficiently obtaining green hydrogen.

There are no quantitative targets for the use of hydrogen in the medium (2030) and long-term (2040 and 2050) periods, which means that the Strategy is not a long-term determinant for the development of this market. The strategy should encourage the participation of Polish enterprises in hydrogen production projects outside Poland, as the domestic supply of green hydrogen may not be sufficient to cover the full demand for hydrogen in the future.

The strategy does not exclude public money support for the production of hydrogen from fossil fuels, which is contrary to the objective of the Hydrogen Strategy itself. Supporting the production of grey hydrogen from natural gas, even with the use of CCS technology, would indirectly subsidize the dependence of the Polish economy on gas imports.

The main elements of the hitherto unresolved legislative problems have been indicated, although the proposed solutions are different from the EU ones.

The final version of the strategy should contain more detailed calculations of the required outlays and financing sources, as well as detailed proposals for the support system for green hydrogen, in line with the schemes currently being developed in the EU. Involving national experts in this work, especially in the legislative and financial sphere, is the only way to work out coherent solutions that can be quickly implemented.

There is a lack of consistency in the basic strategic documents regarding Poland's energy policy. Development forecasts should cover the time horizon until at least 2050, and the balances of production and demand for electricity and hydrogen should be consistent.

One can only hope that further work will lead to consistent solutions and that analyses such as this one will be read and taken into account. At this stage, the most important elements of the legislation should be: the definition of hydrogen, the adoption of criteria for granting state aid for specific types of hydrogen, and the adoption of a regulatory model for the market [41]. Poland is moving away from coal, so low-carbon alternatives are urgently needed. The development of green hydrogen not only offers opportunities to reduce emissions and replace gas in many sectors, it also makes it possible to maintain energy security because green hydrogen complements the energy mix based on renewable sources. The hydrogen strategy is an important first step in this direction.

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