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Opportunities and Limitations of Hydrogen Energy in Poland against the Background of the European Union Energy Policy

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Abstract: One of the strategic goals of developed countries is to significantly increase the share of renewable energy sources in electricity generation. However, the process may be hindered by, e.g., the storage and transport of energy from renewable sources. The European Union countries see the development of the hydrogen economy as an opportunity to overcome this barrier. Therefore, since 2020, the European Union has been implementing a hydrogen strategy that will increase the share of hydrogen in the European energy mix from the current 2 percent to up to 13–14 percent by 2050. In 2021, following the example of other European countries, the Polish government adopted the Polish Hydrogen Strategy until 2030 with an outlook until 2040 (PHS). However, the implementation of the strategy requires significant capital expenditure and infrastructure modernisation, which gives rise to question as to whether Poland is likely to achieve the goals set out in the Polish Hydrogen Strategy and European Green Deal. The subject of the research is an analysis of the sources of financing for the PHS against the background of solutions implemented by the EU countries and a SWOT/TOWS analysis on the hydrogen economy in Poland. The overall result of the SWOT/TOWS analysis shows the advantage of strengths and related opportunities. This allows for a positive assessment of the prospects for the hydrogen economy in Poland. Poland should continue its efforts to take advantage of the external factors (O/S), such as EU support, an increased price competitiveness of hydrogen, and the emergence of a competitive cross-border hydrogen market in Europe. At the same time, the Polish authorities should not forget about the weaknesses and threats that may inhibit the development of the domestic hydrogen market. It is necessary to modernise the infrastructure; increase the share of renewable energy sources in hydrogen production; increase R&D expenditure, and, in particular, to complete the negotiations related to the adoption of the Fit for 55 package.

Keywords: renewable energy; hydrogen economy; Polish Hydrogen Strategy; European Green Deal; SWOT/TOWS analysis

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1. Introduction

The depletion of conventional energy resources, the progressive processes of environmental degradation related to greenhouse gas emissions, and the simultaneous ensuring of countries' energy security mean that accelerating the energy transition is now a major challenge for sustainable industrial development. The unquestionable usefulness of hydrogen in overcoming the barriers and constraints that appear in the implementation of the strategy for energy independence from fossil fuels is the reason why, in 2018, the countries of the European Union set a target for increasing the share of hydrogen in the European energy mix from 2 to 13–14 percent by 2050 [1].

In December 2019, the European Commission launched the European Green Deal (EGD), the EU's new growth strategy that aims to transform the EU economy into a modern, resource-efficient, and competitive one [2]. The main objective of this strategy is to transform the European Union into a climate-neutral area by 2050, i.e., an area completely independent of fossil-fuel-based electricity production. The strategy assumes that a series of measures are introduced, such as legislation review, financial support, research and implementation of new technologies, and the gradual withdrawal of subsidies for fossil fuels and others. The implementation of new technologies based on renewable energy sources requires adjustments in the development of energy storage and transmission infrastructure. High hopes are placed on replacing high-carbon with low-carbon energy and, ultimately, zero-carbon with hydrogen energy. The links between the hydrogen economy and renewable energy do not end with hydrogen participation in energy production and distribution; they also concern the production of hydrogen, where renewable energy makes it possible to supply pure hydrogen for a wide range of applications in the chemical, fertiliser, refinery, and petrochemical industries. Another interesting perspective on hydrogen-powered electromobility in Poland is presented in studies [3].

Hydrogen (the molecular formula H_2) is the simplest and lightest chemical element in the periodic table (atomic number 1). It was first found by the British chemist Robert Boyle (1627–1691) in 1671. Hydrogen atoms make up approximately 91% of the atoms in the Universe. Moreover, hydrogen is estimated to constitute more than 70% of the mass of the solar system [4]. There are three hydrogen isotopes: protium, mass 1, found in more than 99.985% of the Earth's crust; deuterium, mass 2, found in nature in approximately 0.015%; and tritium, mass 3, which appears in small quantities in nature but can be artificially produced by various nuclear reactions [5]. At standard temperature and pressure, hydrogen is a nontoxic, nonmetallic, odourless, tasteless, colourless, and highly combustible diatomic gas. The mass-related energy density of hydrogen is very high: 1 kg of hydrogen contains 132.5 MJ, approximately 2.5 times more energy than is contained in 1 kg of natural gas [6]. Therefore, hydrogen can be used for energy production and storage and is relatively easily transported using a pipeline system and storing in suitable containers. Furthermore, its combustion does not contribute harmful substances to the atmosphere (it is a nonemission fuel). Hydrogen is an efficient energy carrier, but it is not an energy source in itself, so it cannot replace fossil fuels on its own. In its free state, hydrogen is extremely rare in the environment of the Earth. Its use for energy purposes requires it to be extracted from other substances. Liquid hydrogen (LH_2) has the advantage of extreme cleanliness and a more economical type of storage; however, this is at the expense of significant energy consumption of about one-third of its heat of combustion. Due to its small size, and low molecular weight and viscosity, the hydrogen leak rate is 50 times higher than that of water and 10 times higher than that of nitrogen [6]. Hydrogen can be compressed, stored, and piped. However, the small gas molecules that can penetrate the walls of conventional tanks and pipelines require unique materials and storage techniques, implying a further increase in the costs.

Hydrogen production requires using a primary energy source, which is one of the most important obstacles to using it in the energy transition. The primary raw material from which hydrogen is obtained is water (it is obtained by dissociation of water or by water electrolysis). It can also be produced from hydrocarbon fuels (natural gas, coal, and oil). However, the type of primary energy and the processes involved determine the purity of the product. Therefore, using hydrogen in a climate-neutral way raises concerns about how the chemical is produced in the first place. It is a highly energy-intensive process and, if not done using renewable energy, can paradoxically lead to greater use of fossil fuels. In [7], the authors present the results of an economic assessment of four variants of coal gasification into hydrogen (called brown hydrogen) in a shell reactor. The study proves that under Polish conditions, lignite gasification appears to be unprofitable in the imposed scale of total investment expenditures and the current price of coal materials (2020). Fossil-fuel-based hydrogen derived from natural gas is often referred to as grey hydrogen and is the most common type in use today. Low-carbon hydrogen, also called blue hydrogen, is made similarly from natural gas. The CO_2 emitted during production is captured and stored underground, making it a cleaner option with relatively lower emissions [8]. Hydrogen production appears to be the most convenient way to store energy drawn from renewable sources, such as solar or wind energy, which are intermittent by nature [4]. Only the production of green hydrogen is zero emission (almost zero carbon). It is produced in electrolysers using renewable energy (such as wind and solar power). However, the cost of producing it remains high. On average, green hydrogen is two to three times more expensive to produce than grey hydrogen produced from fossil fuels [9].

The European Commission assumes that hydrogen will become one of the leading technologies for the green transition in Europe. The Commission expressed this in its communication on 7 July 2020 entitled Hydrogen Strategy for a climate neutral Europe, which presents the substantive framework and basic assumptions concerning the prospects for building and developing a hydrogen ecosystem in Europe by 2050 [10]. The key European Union document for a strategic initiative related to the development of the hydrogen economy is a European Strategy for Hydrogen adopted by the European Parliament on 19 May 2021 [11].

Koneczna and Cader reviewed the EU countries' strategic documents in the hydrogen economy field. In the first half of 2021, only six EU member states approved the hydrogen strategy (Germany, France, the Netherlands, Portugal, Hungary, the Czech Republic) and two have roadmaps (Spain, Finland) [12]. A study shows that their objectives for 2030 are ambitious and surpass others in terms of employment, CO_2 reduction, value added to the domestic economy, and the installation of RES capacity dedicated to green hydrogen production through electrolysis.

Maj and Szpor show that the Polish hydrogen economy as of 2020 was at a relatively early stage of development [13]:

- Sixty-seven percent of surveyed experts believed that the legal legislation was insufficient for the development of the hydrogen economy;
- Three-quarters of the experts gave a poor assessment of the potential of infrastructure, raw materials, and resources for the implementation of the hydrogen economy;
- Funds allocated to hydrogen R&D in Poland were 40 times lower than the EU leaders (Germany, France);
- The share of funds allocated to hydrogen R&D in total national R&D expenditures was only 2 percent;
- Low research activity—only 83 scientific publications on hydrogen as a fuel (2019).

The Polish Government Resolution No. 149/2021 (dated 7 November 2021) launched the Polish Hydrogen Strategy to 2030 with an outlook to 2040 (PHS) [9]. According to the PHS, a hydrogen economy is defined as "technologies for the production, storage, distribution as well as use of hydrogen and its derivatives, including centralised and distributed systems for hydrogen production, storage, transportation using transmission and distribution grids, other forms of transportation, and its subsequent use in various economic sectors" [14]. The goals of the Polish hydrogen economy are identical to those of the EU energy economy, aiming to ensure stable energy supplies for companies and households and support the implementation of the global project to reduce greenhouse gas emissions and stop global warming. However, according to the study [15], the biggest challenge facing the Polish government appears to be the inconsistency between the legislative changes proposed in the Polish Hydrogen Strategy and the proposals of the European Commission that are not entirely clear or transparent. The author claims that "the lack of a precise vision for European regulation of the hydrogen sector, especially regarding the use and operation of gas or dedicated hydrogen infrastructure, creates uncertainty and poses a serious challenge for the Polish government in preparing future regulations".

The article aims to address the question as to whether Poland is likely to achieve the goals set out in the Polish Hydrogen Strategy and European Green Deal. It presents in a structured and ordered way the legal acts and policy documents included in the study while applying document analysis as a form of qualitative research. Authors used extracted facts and essential elements of the investigated documents to clarify both the national and European context of development of the hydrogen economy in Poland. The article is divided into six chapters. The Section 1 contains the introduction. Section 2 examines the Polish Hydrogen Strategy in the context of the legal, economic, and organisational aspects of developing the hydrogen economy in the European Union. Section 3 is dedicated to the identification of the implementation status of the Polish Hydrogen Strategy. Section 4 deals with the SWOT/TWOS analysis results and their interpretation to provide a situational analysis and enable assessment of the prospects for the hydrogen economy in Poland. Section 5 contains a discussion on the obtained results. Finally, the last section presents the conclusions.

2. Strategies for Developing the Hydrogen Ecosystem

2.1. The Legal, Economic, and Organisational Aspects of Developing the Hydrogen Economy in the European Union

As mentioned above, for the key European Union documents on the hydrogen economy [10], Ref. [11] defines the main objectives, the stages of their implementation, and an outline of the necessary investment processes. According to the adopted strategy, the EU will concentrate its efforts on developing renewable hydrogen production, focusing on wind and solar energy as its basis. Renewable hydrogen meets all the criteria of climate neutrality and is also compatible with an integrated energy system. The use of low-emission hydrogen (mainly by industry) will be transitional and end when the demand for this raw material is fully met. It is assumed that this could occur around 2050, when a quarter of the energy extracted from renewable sources will be devoted to producing renewable hydrogen [11]. At the same time, Europe's ambitions for renewable hydrogen as an important energy carrier are increasing, turning away from the imports of fossil fuels from Russia. The European Commission completed the implementation of the European hydrogen strategy with the publication of the legislative proposal of the REPowerEU Plan in May 2022 [16]. Cumulative investments in renewable hydrogen in Europe could be up to EUR 180–470 billion by 2050, and in the range of EUR 3–18 billion for low-carbon fossil-based hydrogen.

Three phases are assumed to develop the hydrogen ecosystem in Europe (Figure 1).

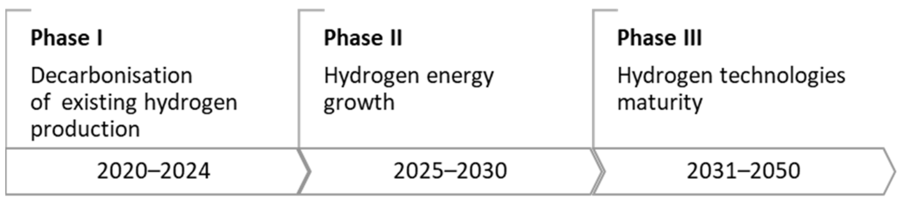

Figure 1. Hydrogen road map for EU. Source: own elaboration based on [11].

A characteristic feature of the first (current) phase to take place between 2020 and 2024 is the emergence of local hydrogen ecosystems, including refineries, steel mills, and large chemical plants, in the vicinity of which high-powered electrolysers (up to 100 MW) are installed, using local renewable energy sources. Any surplus hydrogen production is directed to local refuelling stations, where it is used to power buses, trucks, and other hydrogen fuel cell equipment. It is assumed that by 2024, the electrolysers operating in the EU countries will have a total capacity of at least 6 GW and a production capacity of 1 million tonnes of renewable hydrogen [11]. The European Clean Hydrogen Alliance (ECH2A) was launched on 8 July 2020 in the context of the hydrogen strategy for a climate-neutral Europe [17] to develop plans for further development of clean hydrogen production capacities (with an indication of funding sources). These plans consider the findings of the Next Generation EU Plan [18], including the InvestEU Program, the European Strategic Investment Segment, and the EU Emissions Trading Scheme (EU ETS) Innovation Fund.

The results achieved in this phase will mainly depend on the progress made in establishing and improving the regulatory framework for the hydrogen market.

In the second phase, which will take place between 2025 and 2030, renewable hydrogen will play an essential role in balancing the electricity system based on renewable energy sources. The installed capacity of the electrolysers will reach 40 GW, producing 10 million tonnes of renewable hydrogen [11]. The cost of producing renewable hydrogen will be almost equal to the cost of production based on other technologies. Renewable hydrogen will be used for buffering and energy storage. The operational hydrogen valleys will begin to use the surplus hydrogen to generate heat for residential and commercial buildings after meeting the needs of local industrial and transportation customers. A pan-European network of hydrogen filling stations will be established, and a hydrogen transportation network will be planned. Around 2030, an open, competitive, and cross-border market for hydrogen will be in place in Europe to ensure its efficient allocation to key customer groups.

In the third phase, from 2031 to 2050, hydrogen technologies must reach maturity and become widely available in sectors such as aviation and shipping, industrial and commercial buildings, and housing [16].

At the core of implementing the EU Hydrogen Strategy are not only the EU legal acts that are obligatory for individual member states, but also the entire international institutional and organisational infrastructure that has been promoting and supporting the development of the hydrogen ecosystem for many years. A significant role can be attributed to the Clean Hydrogen Joint Undertaking (JU) (formerly in 2007–2021, the Fuel Cells and Hydrogen Joint Undertaking, i.e., FCH 2 JU, the European Hydrogen and Fuel Cell Technology Platform in 2004–2007). The members of the JU are the European Commission, the fuel cell and hydrogen industries represented by Hydrogen Europe, and the research community represented by Hydrogen Europe Research (103 universities and Research & Technology Organisations (RTO) from 25 countries around Europe and beyond) [19]. The general objective is to support research and innovation activities in solutions and technologies for clean hydrogen under the EU's new funding programme for R&I, Horizon Europe, in synergy with other EU initiatives and programmes [17]. FCH 2 JU funded the publication of the 2019 Hydrogen Roadmap Europe Report, showing why hydrogen is necessary for the energy transition in Europe and how to reach its full potential in order to achieve Europe's 2050 climate targets. On 25 February 2022, the JU adopted the Strategic Research and Innovation Agenda (SRIA) 2021–2027.

Another example of a crucial European initiative that aims to facilitate investments in clean hydrogen is the European Clean Hydrogen Alliance, which was established in July 2020 [17]. The Alliance acts through six roundtables covering all parts of the hydrogen value chain, from production to end use [20]. In addition, the Alliance organises the Hydrogen Forum twice a year for its members. At its third Hydrogen Forum in November 2021, the Alliance published a pipeline of 750 viable investment projects [21] selected from more than 1,000 submitted by the alliance members. The project pipeline provides an overview of hydrogen projects from all parts of the value chain and helps create integrated European hydrogen value chains and profiles projects, including investments in the following:

- Hydrogen production;
- Transmission and distribution;
- Application in industry, transport, energy systems, and buildings.

Since the pipeline was published, the European Commission has entered into agreements with the European Investment Bank and EIT InnoEnergy to advise project promoters on their ability to repay individually and de-risking strategies, investment readiness, and due diligence preparations. They can also invest in individual projects and make profiles for the financial investment community.

One of the most influential global organisations that promotes the development of the hydrogen economy is the Hydrogen Council, a global CEO-led initiative of leading companies in the energy, transport, and industry sectors (more than 130 in 2022), launched at the World Economic Forum in Davos in January 2017 [22]. The Council published the Policy Toolbox for Low Carbon and Renewable Hydrogen report [23] in November 2021, based on an evaluation of the performance of hydrogen policies at different stages of market maturity and value chain segments.

Forty-eight policies were selected on the basis of their economic efficiency and effectiveness, mapping barriers across the value chain and over time. These policies were then grouped into three country architecture policies: self-sufficient hydrogen producers, importers, and hydrogen exporters.

The concerted efforts of the organisations as mentioned above, opinion-formers, and expert groups will undoubtedly increase the chances of a timely implementation of the objectives envisaged in the European Hydrogen Strategy.

2.2. Objectives of the Polish Hydrogen Strategy vs. the EU Climate and Energy Targets

The question remains open whether the economically less prosperous EU countries that currently rely on nonrenewable energy sources will be able to meet the challenges imposed by the strategy. Poland is one of those members. The data on Poland's economic position in the European Union and the situation of the Polish energy sector in 2019 (the year preceding the decade in which the biggest changes in electricity production, distribution, and consumption took place in Europe) show that Poland's GDP accounted for 3.8% of the EU's GDP in 2019. In contrast, Poland's capital expenditure accounted for 3.1% of the annual capital expenditure incurred by the Union [24]. Gross fixed capital formation in relation to GDP in Poland was among the lowest in the Union: in 2019, 18.3% against an EU average of 22.2%. Furthermore, in 2020 and 2021, it decreased to 17.2% and 16.6%, respectively (Figure A1). The group of countries with the lowest capital expenditure in 2019–2021 includes Greece, (10.6%, 11.7%, and 12.9% respectively), Luxembourg (17.6%, 16.8%, 17.3%), Cyprus (18.8%, 19.9%, 17.8%), and Bulgaria (18.6%, 19.2%, 16.6%).

Figure 2 shows the share of renewable energy sources in the total electricity production in Poland in 2015–2020.

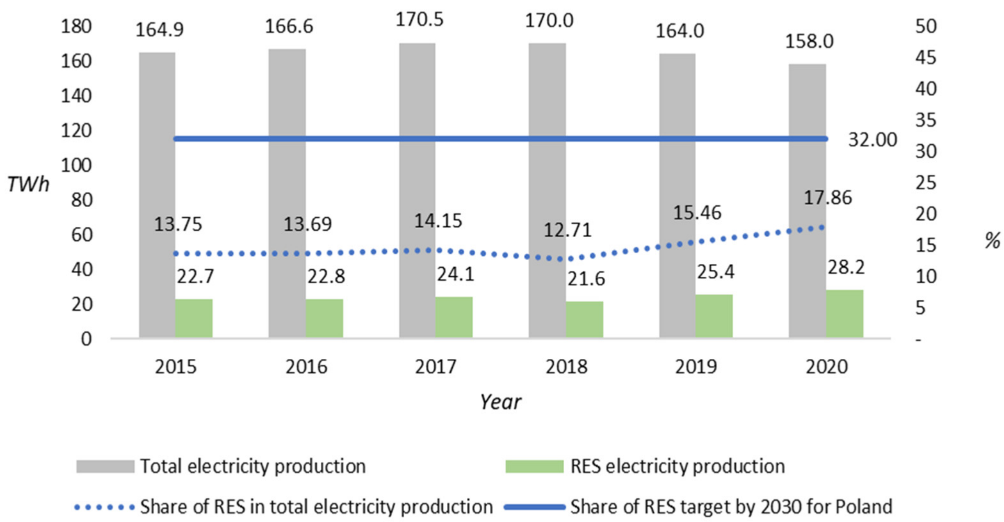

Figure 2. The share of renewable energy sources in the total production of electricity in Poland by sources in 2015–2020. Source: own elaboration based on [25].

The data show a growing trend in the share of RES since 2018 in both absolute and relative terms; however, with 17.9% of the share of RES in 2020, it is still far below the target level of 32% assumed for 2030. The main sources of energy were hard coal and lignite (79.74% of electricity production in 2021) [23], which are characterised by the highest amount of pollutants released into the atmosphere per unit of energy produced. Poland is a signatory to the United Nations Framework Convention on Climate Change (since 1994) and the Kyoto Protocol (2002) and actively supports the international community's efforts to reduce climate change. In the commitment period of 2013–2020 under the Kyoto Protocol, the European Union, its member states, and Iceland were obliged to reduce their average annual greenhouse gas emissions under the joint fulfilment of commitments. The common reduction target was expressed as a commitment to achieve average annual emissions of 80% of the total emissions of all countries in relation to 1988.

In 2020, intensity of greenhouse gas emissions of energy consumption (calculated as the ratio between energy-related GHG emissions and gross inland consumption of energy) compared with that in the year 2000 in the EU ranges from 62.1% in Denmark to 106.6% in Cyprus (Figure A2). In Poland, the rate was 82.2%, while in the EU, the average was 80.8% [22]. Carbon dioxide is Poland's most significant GHG, accounting for 80.7% of national emissions in 2020 [26]. Figure 3 shows a clear trend of decreasing GHG intensity of energy consumption in EU.

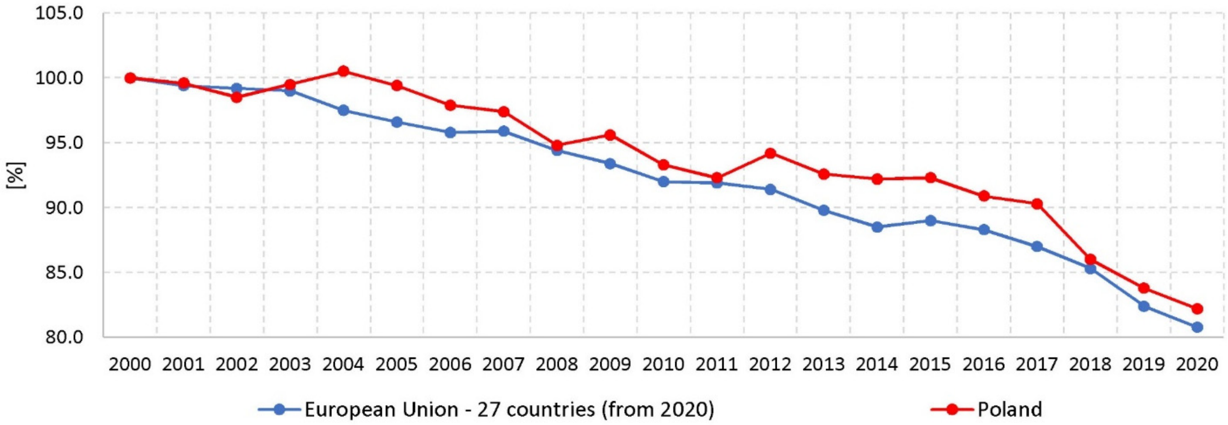

Figure 3. Greenhouse gas emissions intensity of energy consumption. Source: own elaboration based on [27].

As seen in Figure 3, the intensity of greenhouse gas emissions in Poland from 2000 to 2020 follows the trend irregularly and is usually above the EU average. However, since 2018, both indicators have significantly decreased, and the gap between the values analysed is relatively small (1.4 percent point). Further reduction of the intensity of the GHG emissions could be achieved by increasing the share of RES in energy production. In such a case, the chances of achieving the goals related to developing the hydrogen economy and obtaining clean hydrogen as an energy source would also increase. However, building a hydrogen ecosystem would require significant capital expenditure.

The energy transformation process in Poland could be supported by a pool of funds from the European Recovery and Resilience Facility, EU budget for 2021–2027, and the funds provided for this purpose in the Fit for 55 Package. The Package financial mechanisms, which are still under negotiation, should, to a large extent, take into account the economic potential of individual countries on one hand, and the distance separating those countries from achieving the climate targets set by the EU for 2030 on the other. The Package in its current form assumes, e.g., that individual countries will be required to spend 100% of the funds from allowance trading (EU ETS plus allowances for the transport sector and buildings) on energy transformation. The Package also proposes establishing a Social Climate Fund [28] financed from the EU budget and allowance trading (EU ETS), as well as increased resources as part of the Modernisation Fund [29].

Although Poland may be the largest beneficiary of the Social Climate Fund (EUR 13 billion out of the EUR 72 billion that the Fund will have at its disposal in the years 2025–2032), it is one of the strongest critics of the Package and the EU's energy transition policy. This is reflected, for instance, in the Polish Parliament's resolution adopted in December 2021, which calls on the EU countries to suspend the EU ETS, and in the statements of leading politicians of the Eurosceptic governing party, directly contesting the sense and objectives of the Fit for 55. The Polish authorities argue that the investment needed to rebuild the Polish energy sector by 2030 (including investment in developing a hydrogen ecosystem) would have to be so high that it would lead to a sharp increase in energy prices, economic collapse, and a significant reduction in living standards. An additional argument is the increase in energy prices is caused by the war in Ukraine.

The Polish Hydrogen Strategy (PHS) [14] is consistent with the key legal acts regulating the development of the energy sector in Poland until 2040:

- Strategy for Responsible Development until 2020 (with an outlook to 2030) [30];
- The Act on electromobility and alternative fuels [31];
- The Energy Policy of Poland until 2040 (PEP2040) [32];
- Poland's National Energy and Climate Plan for the years 2021–2030 (NECP2030), developed in fulfilment of the obligation set out in Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action submitted to the European Commission on 30 December 2019.

According to NECP2030, primary climate and energy targets are as follows [33]:

- A 7% reduction in greenhouse gas emissions from sectors not covered by the EU ETS compared with 2005 levels;
- A 21–23% share of RES in gross final energy consumption (taking into account the percentage share of RES in transport and the annual increase of the share of RES in heating and cooling by 1.1 percentage points on average per year), provided that Poland is granted additional EU funds, including those earmarked for a just transition;
- A 32% share of RES in electricity production;
- Increase in energy efficiency of 23% in comparison with the PRIMES 2007 projections;
- Reduction of coal share in electricity production to 56–60%.

The NECP2030 plan considers hydrogen mainly as a means to develop energy-efficient and low-emission transport (development of electromobility).

The goals adopted in the NECP2030 already assume an increase in EU aid for their implementation. Meanwhile, on 30 July 2021, the European Parliament and the European Commission adopted a new legal act, the European Climate Law [34], which is the legislative basis of the Fit for 55 package and significantly changed the climate targets set out in Regulation (EU) 2021/1119.

Poland's approval of these targets would mean a fundamental change in the attitude towards energy policy, a significant increase in expenditure on its implementation, and a total reconstruction of the National Energy and Climate Plan for 2021–2030, with subsequent repercussions for the PHS.

The PHS in its present form is the result of analyses, studies, and actions that have already been carried out in Poland in connection with the need for a radical change in the energy mix. However, it is also the result of the coordination of activities undertaken within the European Union that have led to, e.g., the participation of Polish entities in the European Clean Hydrogen Alliance or the participation of Poland in the Important Projects of Common European Interest (IPCEI). IPCEI in the fields of low-emission and renewable energy-produced hydrogen is another European undertaking in the field of modern energy (after IPCEI in the battery industry) involving Poland. The joint initiative aims to build a hydrogen value chain in the EU that will enable its use in transport, energy, and industry.

According to the PHS, its main objective is to create and develop the Polish hydrogen industry in order to achieve climate neutrality and maintain the competitiveness of the Polish economy [14]. Due to this, the strategy aims to develop national competencies and technologies for developing a low-carbon hydrogen economy (especially the energy, transportation, and industry sectors) and a necessary legal framework. This is to be achieved through the six objectives:

1. The deployment of hydrogen technologies in the energy sector;
2. The use of hydrogen as an alternative fuel in transport, which will enable the transition to a low-carbon transport sector;

3. Supporting the decarbonisation of industry—the use of low-carbon hydrogen will significantly reduce greenhouse gas emissions, especially in sectors that are difficult to electrify;
4. Launching hydrogen production in new installations—providing conditions for launching installations to produce hydrogen exclusively from low- and zero-emission sources (governmental incentives will provide support for innovative activities that will enable Polish entrepreneurs to benefit from the EU aid and international financial institutions for hydrogen development);
5. Ensuring efficient and safe hydrogen transmission, distribution, and storage;
6. Creating an appropriate and standardised legal framework, which would enable, among other things, a gradual increase in the use of renewable energy for hydrogen electrolysis; elimination of barriers to hydrogen market development.

The PHS foresees 44 actions (including two horizontal measures) to achieve its objectives. The implementation process has been divided into two stages: the first by 2025; the second by 2030. Some of the measures are purely quantitative while others are operational, meaning the launch or development of another area of the hydrogen economy. The 2025 quantitative measures should result in the following:

- Launching a P2G installation of at least 1 MW class;
- Implementation of 100 to 250 new zero-emission hydrogen buses;
- Launching at least 32 new hydrogen filling and bunkering stations at pressures of 350 and 700 bars;
- Launching an installation for producing hydrogen from low-emission sources, processes, and technologies with the capability at least of 50 MW.

By 2030, the following developments should be in operation:

- Cogeneration and polygeneration installations (e.g., combined heat and power plants) with a capacity of up to 50 MWt, where hydrogen will be the primary fuel; 800 to 1000 new hydrogen buses (including those manufactured in Poland);
- At least five hydrogen valleys, which will be centres of excellence in the process of implementing a hydrogen economy;
- Not less than 2 GW of installed production capacity (including electrolysers) for producing hydrogen and its derivatives from low-emission sources, processes, and technologies.

Qualitative measures are defined more broadly in the PHS. By 2025, the aims are as follows:

- To develop hydrogen purification plants compliant with the EU standards in force;
- To implement hydrogen trains/locomotives to replace their diesel counterparts on routes not intended for electrification;
- To launch pilot programmes for applying hydrogen and its derivatives in urban, heavy-road, maritime, river, air, and intermodal transport;
- To carry out activities to obtain and use low-carbon hydrogen for petrochemical, chemical, and fertiliser production processes based on green industrial energy;
- To launch technological pilot projects for sectors where climate neutrality is difficult to achieve (steel, refining, chemicals);
- To develop hydrogen transmission and distribution networks based on an analysis of the optimal form of transmission;
- To produce a feasibility study of a north–south hydrogen pipeline (the Hydrogen Highway);
- To implement rail, road, and intermodal hydrogen transport.

Among the main actions planned by 2030 are the following:

- Further development of hydrogen refuelling and bunkering infrastructure;
- Gradual replacement of diesel trains and locomotives by their hydrogen equivalents;
- Development of hydrogen use in heavy-wheel, rail, sea, river, air, and intermodal transport;
- Commissioning of vessels with hydrogen-based propulsion systems;

- Adaptation of selected sections of the gas network for the transmission and distribution of hydrogen mixed with gas;
- Introduction of synthetic natural gas (SNG) produced in power-to-gas (P2G) systems into gas networks, as well as the construction of pipelines for the transmission and distribution of hydrogen;
- R&D on lightweight tanks for hydrogen production and development of large-scale salt caverns for hydrogen storage.

The most striking observations that emerge from the comparison of activities in developing the hydrogen economy in Poland and the recommendations of the European Union are as follows:

- The first phase of planned activities in Poland closes in 2025, while in the regulations of the EU it lasts one year shorter (until 2024), which necessarily indicates a greater intensity of activities at the very beginning of the implementation of the hydrogen strategy.
- The EU strategy is strongly focused on obtaining zero-emission hydrogen as an energy source, whereas projects to obtain low-emission hydrogen for energy purposes predominate in the PHS.
- The EU Hydrogen Strategy contains precisely outlined goals in terms of the construction of a technical base (the power of installed electrolysers) and the volume of renewable hydrogen production (in a million tonnes), which is not the case with the PHS; instead, the latter contains only quite enigmatically formulated quantitative goals concerning developing a technical base for hydrogen production, assuming, for example, that the capacity of installations for producing low-emission hydrogen, including electrolysers, should be at the level of 2 GW.

2.3. Changes Announced in Polish Energy Strategy

The challenges posed by the EU Regulation (EU) 2021/1119 to the Polish energy policy have been strengthened in connection with the war in Ukraine. As a consequence, the state authorities announced a quite significant change in the priorities of this policy. The speed with which the authorities responded to the change in the external conditions for the functioning of the energy sector is worth highlighting. The current version of the Polish Energy Policy (PEP2040) was approved by the Council of Ministers on 2 February 2021, while the assumptions for its update were adopted on 29 March 2022 [35]. The new regulations may also provide an opportunity to accelerate the development of the hydrogen economy in Poland and bring its profile closer to the strategy implemented in the European Union. This applies in particular to the proportion of zero-emission and low-emission hydrogen in the production of this raw material. The proposed changes to PEP2040 go in three directions:

1. Increased share of renewable energies in final energy consumption (over the current level of 23 percent in 2030);
2. Modernisation of small power plants (200 MW) with coal and iron to extend their service life;
3. Development of the nuclear power industry.

At the time of publishing, no information was available on the new share threshold of RES for electricity generation in 2030. The authorities will aim to accelerate the integration of the national RES system into the EU system. In addition to further developing wind and solar power capacity, efforts will be intensified to develop weather-independent RES, i.e., using water, biomass, biogas, or ground thermal energy. Especially desirable is the use of RES in energy clusters, energy cooperatives, and hybrid installations. For gaseous fuels, measures will be taken to replace the demand for natural gas with decarbonised gases, including the development of hydrogen technologies, which are a viable alternative to the use of natural gas. To reduce the demand for liquid fuels, alternative energy sources in transport, mainly hydrogen, will be intensified.

The update of PEP2040 will include a plan for using existing energy generation units, considering the possibility of increasing the efficiency and lifetime of coal-fired units, together with the necessary modernisation and maintenance measures. This applies in particular to nearly 50 units with a capacity of 200 MW (their total capacity is about 10 GW). Modernisation of these units will enable their use with better operating parameters and lower environmental impact, affecting the economic rationale for their use. These investments will also ensure better conditions for integrating RES into the power system by securing an appropriate power reserve.

The main strategic objective of the Polish nuclear power sector will remain the completion of the first nuclear power plant based on large power reactors (above 1000 MW) and the comprehensive implementation of the Polish Nuclear Energy Program. In parallel, efforts will be made to develop the concept of creating the legal, technical, and capital basis for the construction of a system of micro, small, and medium modular (nuclear) reactors (SMRs, MMRs) and using them in a slightly longer time perspective as a source of support for the electricity system. Furthermore, as is the case with the modernisation of coal-fired units, investments in nuclear energy will also contribute to better conditions for integrating RES into the power system due to the guarantee of an adequate power reserve. The use of this technology for process heat generation may serve as an alternative to conventional units in industry and heating. In the energy sector, these distributed units (without replacing large nuclear units in the system) can become additional diversification elements of the electricity generation structure and constitute a factor in strengthening security at the local level.

The PEP2040 update also assumes intensified efforts related to developing energy storage facilities, including pumped storage hydroelectric power plants and prosumer storage facilities, which will reduce the effects of potential disruptions in energy generation or transmission. In the long term, hydrogen, especially from RES, will play a unique role in storing energy and ensuring the management of surplus energy generation from RES.

3. Implementation Status of the Polish Hydrogen Strategy

3.1. Construction of Hydrogen Management Infrastructure

The specificity of Poland regarding the development of a hydrogen economy is that it is one of the leading hydrogen producers in Europe (third place after Germany and the Netherlands with an annual production of about 1.3 million tonnes) [14], yet, it produces negligible amounts of hydrogen obtained by electrolysis of water using wind and solar energy, which is the main priority of the EU hydrogen strategy. Reforming biogas or biomethane, as well as the sustainable biochemical conversion of biomass, also provides little clean hydrogen. In 2020, almost 95% of the hydrogen in Poland was produced from fossil fuels by reforming natural gas steam, partial oxidation of methane, and coal gasification (76% on average worldwide) [14]. The question that remains open is how Poland could use its position as a leading producer of hydrogen both to meet its inland growing demand for hydrogen energy and that of its partner countries. The Hydrogen Strategy officially implemented by Poland assumes a hybrid solution to this problem, consisting of adopting a medium-term (until 2030) course of development of hydrogen production based on low-emission technologies (carbon footprint below 5.8 kg CO_2 eq/kg H_2) with a gradual increase in the share of zero-emission hydrogen in the long term (until and beyond 2040). Adopting such a solution will undoubtedly ensure more rational use of domestic fossil fuel resources. However, it does not mean that Poland will maintain its current position in the European market of hydrogen producers/exporters, even though the total hydrogen market in Poland shows quite a high growth dynamic (a 35% increase in 2015–2022, with a value of about EUR 128 billion at the end of the period is assumed) [36].

The main barrier to further growth in low-emission hydrogen production is the EU Emissions Trading Scheme (ETS), resulting in a systematic increase in the price of Carbon Emission Allowances (Figure A3), raising the cost of raw material per tonne and decreasing profitability of its production. The price of EUA on 24 February 2022 was EUR 88, while in 2019, the average price was EUR 24.7 (an increase of 256%). This is partly because the ETS structure requires a long-term rise in EUA prices as the supply of these permits decreases year by year. However, the demand for EUA is also decreasing (e.g., replacing conventional power plants—consumers of emission allowances—with renewable energy sources) but more slowly than the supply. Currently, this occurs at a rate of 2.2% per year, but according to the Fit for 55 package, the withdrawal of allowances will be accelerated to 3.7–4.2% per year. The Fit for 55 package will accelerate the price of EUA, which the market will finally set, while EU regulations do not specify their desired level explicitly and Market Stability Reserve (MSR) interventions, on the other hand, are discretionary. Therefore, EUA price forecasts vary from EUR 80 to EUR 129 per tonne of CO_2 in 2030 [30].

The main centres for obtaining hydrogen for energy purposes in Poland will be the hydrogen valleys which, according to the EU Hydrogen Strategy, are to become a coherent element of the European Hydrogen Ecosystem. A minimum of five hydrogen valleys have been created or are in the process of being created (in the European Union, 20 hydrogen valleys were operating in mid-2021). The coordinator of the process of creating hydrogen valleys in Poland is the Industrial Development Agency JSC. The Polish Ecosystem of Innovation of Hydrogen Valleys includes innovative industrial undertakings, investment projects of large, long-term scale implemented in specific areas (Table 1).

Table 1. Key hydrogen valleys in Poland (as of March 2022).

Hydrogen Valley	Date of Establishment	Statutory Objectives
Pomeranian	1 October 2019	Building a hydrogen ecosystem in the Pomeranian region, implementing projects related to land and sea transport (buses, trains, and ships powered by hydrogen) and connecting the ports of Tri-City and Hel. Developing 'power-to-gas' projects in the Pomeranian region. Raising hydrogen awareness among the inhabitants of the voivodeship.
Sub-Carpathian	18 May 2021	The estimated potential of the programme is at least 20,000 tons of hydrogen per year and a 15% share of hydrogen as a fuel in the transport energy mix of the Pomeranian region by 2030.
Greater Poland	5 July 2021	Producing fuel cells, hydrogen buses, and work on hydrogen as a fuel to power aircraft.
Silesian-Lesser Poland	31 January 2022	Cross-sectoral cooperation for the dissemination of hydrogen solutions and the production of green hydrogen.
Lower Silesian	25 February 2022	Supporting the development of hydrogen economy, building the Silesian-Lesser Poland hydrogen industry based on the production of hydrogen in the electrolysis process with the use of energy produced from RES installations and its use in the energy sector, including heat, transport and infrastructure, and industry.
Mazovian	8 April 2022	Creating economic networks with suppliers, subcontractors, and collaborators, especially between universities, research institutes, start-ups, clusters, implementation companies, local government units, and large state-treasury companies.

Source: own study based on [37,38].

Leading national manufacturing, energy, and transport companies as well as with local self-governments, universities, research institutes, associations established to rebuild the energy sector, environmental and logistics companies, and others are actively involved in the organisation of hydrogen valleys in Poland. In addition to projects covering one or two large regions (e.g., Silesia and Lesser Poland), hydrogen valleys covering the economies of small urban centres (e.g., the Sanok Hydrogen Valley in Sub-Carpathian voivodship) are being created. Despite dynamically progressing organisational works, it is difficult to assume that hydrogen valleys in Poland will be able to achieve by 2024 the same production and distribution capacity as in more technically advanced European Union countries, where it is planned to install electrolysers with a capacity of at least 6 GW with a production capacity of 1 million tonnes of renewable hydrogen. It is also difficult to predict that the Polish hydrogen valleys will enable the creation of large ecosystems by 2030 (including refineries, steel mills, and large chemical plants) using high-power electrolysers (up to 100 MW) and local renewable energy sources as the basis for energy production. One of the critical reasons for the delays in building the Polish hydrogen ecosystem is inadequate funding.

3.2. Financial Aspects of the Implementation of the PHS

According to PEP2040, investment expenditure related to the reconstruction of the fuel and energy sector in Poland in 2021–2040 is expected to amount to approximately PLN 867–880 billion (about EUR 190 billion, at an exchange rate of PLN 4.6 per EUR 1). However, the material scope of these expenses is broad, covering, in particular, the financing of the construction of the first Polish nuclear power plant with a capacity of 1.6 GW by 2033 and another five units of similar size at intervals of 2–3 years [14]. On the other hand, the expenditure on developing the hydrogen ecosystem (especially until 2030) will constitute only a small part of these funds for several reasons, as follows:

- The need to meet the demand for energy by using cheaper (but more harmful to the environment) sources of its acquisition;
- Still relatively low level of advancement of hydrogen technologies, which limits the possibilities of investing in their implementation;
- Lack of a comprehensive and precise plan to build a hydrogen ecosystem in Poland (PHS does not fill this gap sufficiently).

PHS provides a very rough estimate of the expenditure needed to meet its objectives. Until 2025, these investments will be directed at the implementation of hydrogen technologies in public transport, the construction of hydrogen refuelling infrastructure, and the launch of installations for the production of low-emission hydrogen. These expense figures are estimated at PLN 930 million (about EUR 200 million). Furthermore, the construction of low-emission hydrogen production facilities (especially electrolysers with a total capacity of 2 GW) will continue until 2030; therefore, it will constitute the main part of the costs incurred for developing the hydrogen ecosystem (about PLN 9 billion out of the total outlays of PLN 10.8 billion, i.e., about EUR 1.96 billion and EUR 2.35 billion, respectively) [14].

However, in Poland, low-emission hydrogen (even produced in modern electrolysers) is not currently price-competitive compared with fossil hydrogen because of the high energy cost needed. Therefore, the condition for the viability of the electrolyser construction program is the achievement of adequate capacity and efficiency of the offshore wind farm construction program, ensuring electricity supply at a price lower than PLN 200/MWh, i.e., about EUR 43.5/MWh (estimates from October 2021). In this case, the price of hydrogen production in electrolysers powered by offshore wind farms could be approximately PLN 13.5/kgH_2, i.e., about EUR 2.9/kgH_2; so, it could be reduced by half compared to the current theoretical price of hydrogen obtained from this source [9]. Therefore, a larger scale of action is needed to improve offshore wind farm technological and economic efficiency for the program to produce satisfactory results. However, an obvious benefit of the offshore wind farm hydrogen production from electrolysers would be an improvement in the proportion of hydrogen produced, with a more significant proportion of zero-emission hydrogen (which is in line with the EU priorities).

Financial problems should not be a major obstacle to the timely implementation of the PHS concerning the implementation of hydrogen technologies in public transport (hydrogen buses) and refuelling infrastructure [39]. This is due to two factors:

1. The steady decline in the price of hydrogen fuel will make the cost of operating fuel cell buses equal to the cost of operating electric buses around 2025;
2. The largest Polish fuel and energy company PKN Orlen S.A. is interested in increasing hydrogen fuel sales.

Improving the cost competitiveness of hydrogen buses makes the Polish company Solaris the largest producer of battery and hydrogen buses in the European market, with a 15.1% share in 2021. Large Polish cities (e.g., Krakow, Poznan, Gdansk, Katowice) are currently testing these buses and will put them into service soon. Furthermore, the development of hydrogen-based public transport (and private transport) encourages the biggest Polish fuel distributor PKN Orlen to build its hydrogen distribution network. In May 2022, the first public hydrogen filling station was launched in Krakow. By 2030, Orlen plans to launch 57 such stations in Poland [40].

A key element in building a hydrogen ecosystem in Poland will be the development of a network for the transmission and supply of hydrogen to industrial and municipal customers. Adapting existing natural gas pipelines to transmit hydrogen and construction of infrastructure dedicated solely to hydrogen transportation will require significant capital expenditure. No estimates of their scale are currently available. However, it is known that the current technical condition of Polish gas pipelines does not allow for their profitable adaptation to hydrogen transmission over a more extended period.

The Polish Hydrogen Strategy 2030 contains 12 programmes of financial support to achieve its goals:

1. Programmes supporting conceptual work, research, and development in the field of hydrogen technologies (two in total);
2. Programmes supporting entrepreneurs, business environment institutions, research and development units, and public administration institutions carrying out innovative projects related to hydrogen technologies and implementing works in the field of production technology, transport, storage, and use of emission-free hydrogen (four in total);
3. EU Programmes dedicated in their entirety or including components aimed at developing the hydrogen ecosystem in EU countries (a total of six).

The financial capacity of all programmes using mainly national funds for developing the hydrogen economy and launched in 2021 is estimated at just over PLN 2 billion (EUR 435 million), including the following:

- The National Centre for Research and Development Hydrogen Technology Support Program (PLN 1 billion) and the National Fund for Environmental Protection and Water Management (NFEPWM, PLN 600 million);
- Green Public Transport (PLN 320 million);
- Support for electric vehicle charging and refuelling infrastructure (ca. PLN 100 million);
- The NFEPWM Hydrogen Economy—no financial data available yet.

Although the approximate value of the budgets of individual national programmes is known, it is difficult to estimate the value of funds that Poland can obtain for these purposes from the European Union, which includes financial support from the following:

- The Important Projects of Common European Interest (IPCEI);
- The Instrument for Recovery and Resilience (Reconstruction Fund);
- The Fair Transition Mechanism, Cohesion Policy Funds, and the Connecting Europe Facility (CEF).

The dedicated hydrogen funds of the Polish Reconstruction Plan (adopted as IPCEI projects) alone are worth EUR 800 million, nearly double the amount that national programmes could allocate. However, the inflow of EU funds under the Polish Reconstruction Plan may be delayed by the ongoing dispute between the Polish government and the EU institutions under the slogan "Money for Rule of Law". Prolonging this dispute means further delays in achieving the PHS objectives.

4. The SWOT/TOWS Analysis of the Hydrogen Economy in Poland

In order to find an answer to the question of whether Poland has the chance to achieve the goals set out in the Polish Hydrogen Strategy and European Green Deal, a SWOT/TOWS analysis on hydrogen economy in Poland has been carried out. The proposed method is one of the techniques used for strategic diagnosis, which, in its essence, serves to search, collect, and organise data on factors that determine and affect the organisation, system, process, project, or product, presented in a clear and legible form. In the study, the proposed analysis will help to diagnose and determine the best direction for the development of the Polish hydrogen market in the context of the impact of both external and internal factors.

The analysis begins with identifying the strengths and weaknesses of the hydrogen market in Poland, but also recognising emerging opportunities and threats from the environment—an approach commonly known as the SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis. The identified factors affecting the hydrogen market in Poland were classified into sets and assigned weights, creating a matrix consisting of four fields S/W/O/T (Table 2). The levels of weights were determined according to the authors' knowledge about the potential impact of individual factors. The next step was to identify the interactions between the factors classified into each category (Table A1). Then, the TOWS analysis (which is the inversion of the SWOT acronym) was performed (Table A2). This method makes it possible to analyse the opportunities and threats in the environment facing the hydrogen market in Poland and confront them with the predispositions (strengths/weaknesses) of this market to exploit the opportunities and mitigate the threats.

Table 2. The factors of the SWOT/TOWS analysis of the hydrogen economy in Poland and their weights.

No.	Internal Factors (S—Strengths)	Weight	No.	Internal Factors (W—Weaknesses)	Weight
S1	Assigning hydrogen, in particular zero-emission, a special role in storage and RES energy management (PEP2040 update).	0.5	W1	Poland's low investment capacity compared with that of leading European Union countries, limiting the possible scale of investment in hydrogen power development; inadequate R&D funding.	0.3
S2	Growing hydrogen generation capacity. There will be six hydrogen valleys, which will be the main centres for obtaining hydrogen for energy purposes and parts of the European Hydrogen Ecosystem.	0.1	W2	High greenhouse gas emission intensity of energy consumption.	0.1
S3	Intensified efforts to develop offshore wind farms and pumped storage hydroelectric power plants that will enable increased production of zero-emission hydrogen.	0.15	W3	Very low production of hydrogen obtained by electrolysis of water, carried out using wind and solar energy. In 2020, nearly 95 percent of hydrogen in Poland was produced from fossil fuels.	0.25
S4	No financial problems with the timely implementation of the PHS in the part concerning the implementation of hydrogen technologies in public transport (hydrogen buses) and refuelling infrastructure.	0.25	W4	Lack of price competitiveness in Poland of low-emission hydrogen (even produced in modern electrolysers) with hydrogen obtained from fossil sources due to the high cost of energy needed for its production.	0.1
			W5	No infrastructure (gas pipelines) dedicated solely to the transport of hydrogen.	0.25
-	**External factors (O—Opportunities)**	-	-	**External factors (T—Threats)**	-
O1	Establishment of an open, competitive, cross-border hydrogen market in Europe around 2030, ensuring its efficient allocation to key groups of recipients.	0.4	T1	Lengthy negotiations related to the adoption of the Fit for 55 package.	0.4

Table 2. *Cont.*

O2	A rapid improvement in the price competitiveness of hydrogen obtained in electrolysers powered by offshore wind farms vis-à-vis hydrogen obtained from fossil sources due to strong price increases for all fossil energy feedstocks, including coal.	0.2	T2	Significant reductions in the supply of fossil energy resources and price increases on world markets.	0.2
O3	Continuous decline in hydrogen fuel prices, bringing fuel cell bus operating costs in line with the operating costs of electric buses around 2025.	0.1	T3	Increased costs and deterioration in the cost-effectiveness of low-emission hydrogen production associated with the systematic increase in the EU ETS price.	0.3
O4	Financial support from the EU for the implementation of the PHS objectives.	0.3	T4	The need for very high energy production costs in the event of further expansion and price increases of the EU ETS.	0.1

Source: own elaboration.

The SWOT/TOWS analysis is concluded with a summary of the results (including the number and weighted number of interactions, which is the sum of the SWOT and TOWS linkages) presented in Table A3. The summary also features an interpretation of the results, indicating the type of strategy that is most appropriate for the hydrogen market in Poland.

There are four combinations of analysis factors and corresponding action strategies [41,42]:

- maxi-maxi (S/O)—strengths and opportunities prevail, corresponding to a strategy of strong expansion and diversified development; it is the strategy with the greatest potential for success.
- mini-maxi (W/O)—weaknesses prevail, but it is favoured by the system of external conditions (opportunities). The strategy is to exploit the favourable external environment while reducing or improving the weaknesses—the negative internal factors.
- maxi-mini (S/T)—strengths and threats prevail, the source of barriers to development is the unfavourable pattern of external conditions. The strategy is to use strengths, assets, and internal potential to counter the threats present in the environment.
- mini-mini (W/T)—predominance of weaknesses (low internal potential) and threats (unfavourable external conditions). The strategy boils down to a struggle for survival and the resolution of crises; it is the least favourable strategy.

Two sets of test questions were used to determine the nature of the relationships between individual factors, defining them as existent (1) or nonexistent (0):

- In the SWOT analysis:
  1. Does a particular strength make it possible to exploit an opportunity?
  2. Will a particular strength help to mitigate a given threat?
  3. Does a specific weakness limit the possibilities of using a given opportunity?
  4. Does a specific weakness increase the risk associated with a given threat?
- In the TOWS analysis:
  1. Does the opportunity reinforce a given strength?
  2. Does the threat undermine the strength?
  3. Does the opportunity make it possible to overcome the weaknesses?
  4. Does the threat compound the weaknesses?

The analysis of the W/T combination shows the weakness of the potential associated with the production of hydrogen in Poland, which means that the risks from the environment may exert an increasing negative impact on this production. The weakness of the potential is also evidenced by the W/O combination, indicating that external opportunities may be limited by weaknesses in the hydrogen economy in Poland.

As the differences between the W/T, W/O, and S/O combinations are relatively small, it is worth extending the SWOT analysis to include the TOWS procedure. The procedure gives an unambiguous result. The highest sum of interactions (14 per 35 interactions, i.e., 40% of all interactions) and weighted sum of interactions (7.1) are provided by the O/S combination. This demonstrates the very strong positive impact of opportunities from the external environment on the strengths of the hydrogen market.

This overwhelmingly positive impact of opportunities from the external environment on the development of the hydrogen economy fully offsets the negative impact of the W/T and W/O combinations, so that the aggregate result of the SWOT/TOWS analysis indicates that strengths and associated opportunities prevail. This allows for a positive assessment of the prospects for the Polish hydrogen economy. Poland should continue its efforts to take advantage of the opportunities arising from the environment (O/S), such as EU support; improvement of the price competitiveness of hydrogen; and the emergence of a competitive, cross-border hydrogen market in Europe. At the same time, the Polish authorities should not forget about the weaknesses and threats that may inhibit the development of the domestic hydrogen market. It is vital to modernise the infrastructure; increase the share of renewable energy sources in hydrogen production and increase R&D expenditure; and, in particular, to complete the negotiations related to the adoption of the Fit for 55 package.

It should be emphasised that the presented analysis is not perfect or comprehensive, but it is a fundamental tool of strategic analysis, and its results can be treated as a guide in conducting deeper research on the discussed issue. It is beyond doubt that the elements of the SWOT analysis with regard to the hydrogen economy in Poland (its strengths, weaknesses, opportunities, and threats) should be continuously updated. This is caused by the early stage of development of the hydrogen market, whose potential is highly dependent on the external environment, which is currently undergoing strong changes.

5. Discussion

The adoption of the Polish Hydrogen Strategy 2030 by Poland in November 2021 completed a certain stage of work to include this country in the construction of the European hydrogen ecosystem. However, the way in which Poland would participate in this project outlined in the strategy, which is so important for the development of the European energy sector, may raise some reasonable doubts. The doubts arise both in connection with the "profiling" of the strategy on the development of low-emission hydrogen production (the Union bets on the development of zero-emission hydrogen) and the failure to take into account the goals adopted in the Fit for 55 Package, despite the fact that these goals were already officially known as of 30 July 2021.

The text of the strategy shows that it is entirely consistent with the Polish legal acts concerning the development of the energy sector, especially the National Energy and Climate Plan for 2021–2030 (NECP2030) and the PEP2040. As stated above, the PEP2040 is to be updated shortly so the NECP2030 and the PHS should also be updated, at least to the extent that the targets and planned actions defined in those documents correspond to those set out in the new version of the PEP2040. However, it would mean implementing only the minimum program. The state authorities, deciding on the reconstruction of the Polish energy sector, should first re-evaluate their attitude towards the schedule of shifting from fossil energy sources to renewable sources. According to the current state of the law, Poland will strive to achieve a 32% share of RES in electricity and a 28% share in heat by 2030, while the EU targets, provided for in the Fit for 55 package, assume shares of 40% and 39.4%. As a result, the share of coal in electricity generation will remain at a level of approximately 56% in Poland in 2030, while the EU targets assume a complete withdrawal from coal around 2030. Only seven countries in the European Union want to continue to use coal to generate electricity after 2030—these are Bulgaria, Croatia, the Czech Republic, Germany, Poland, Romania, and Slovenia. However, Poland's share of the use of coal in the EU's electricity generation will be by far the largest. Consequently, Poland, as a country with the highest share of coal in the energy mix in the EU, will continue to occupy the leading position in greenhouse gas emissions, calculated per unit of GDP produced (in tons of equivalent CO_2/EUR billion GDP) [43].

This, in turn, will translate into a further increase in the share of CO_2 emission allowance costs (in the first quarter of 2022, this share was already at a level of approximately 60%!) and further growth in electricity prices. If the EU ETS trade continues in the coming years, in line with the regulations adopted in the European Climate Law (ECL), Poland will be forced to pass on the costs of its lack of decisive actions with respect to shifting electricity production from coal to RES to its citizens. An alternative to such a scenario could only be Poland's withdrawal from European programmes aimed at achieving climate neutrality by 2050 or from the EU ETS alone, which is a possibility contemplated by the ruling right-wing party coalition. However, this does not seem feasible for the following reasons:

- If Poland fails to implement the Fit for 55 findings, this will set a dangerous precedent, contesting one of the most important EU goals that the Community has been consistently pursuing for several decades, which could expose Poland to severe repercussions from the Community;
- By withdrawing from the EU ETS, Poland would reject the EU's key instrument to pressure member states to move away from high-carbon energy sources, which would result in the EU significantly limiting funds flowing to Poland for energy restructuring (e.g., the Modernisation Fund). In addition, the EU could argue that Poland is not sufficiently engaged in implementing the EU energy targets.

It seems that a better solution would be a thorough analysis, evaluation, and modification of Poland's plans for the reconstruction of the energy sector so that they comply with the EU objectives, especially the arrangements and regulations that will be brought by the final adoption of the currently negotiated Fit for 55 Package. The numerous benefits of such a solution for Poland are indicated in a report published by Bank PeKaO S.A. [44]. Assuming that the negotiations may take 2 to 3 years, there will be enough time to fully coordinate the Polish objectives and actions with those of the EU. The effect of this coordination should be, on the one hand, a significant acceleration of Poland's transition from coal as a basis for the electricity sector and, on the other hand, keeping pace with the European Union in the field of implementation of solutions based on RES, including production of emission-free hydrogen. Furthermore, such actions would be fully in line with the Fit for 55 regulations.

Therefore, it is highly probable that Poland would be in a favourable negotiating position in its efforts to obtain additional EU financial support for the construction of the hydrogen ecosystem, which—according to the SWOT/TOWS analysis—would definitely increase the chances of implementing this project.

6. Conclusions

Conducting research in the current period on the conditions and prospects for Poland's implementation of a hydrogen strategy is severely hampered for at least three reasons:

1. The war in Ukraine, which has caused changes in the supply of energy resources and their prices on a European and global scale that were difficult to predict in advance;
2. The escalation of the dispute between Poland and the European Union over the rule of law is reflected in financial penalties imposed by the Union on Poland and the suspension of EU funding under the Instrument for Reconstruction and Enhanced Resilience (Reconstruction Fund) for Poland;
3. The development of inflationary processes in Poland (annual price growth rate of 15.6% for June 2022) makes it very difficult to plan expenditure and effects in the power sector in a longer time horizon (up to 2030).

The research shows that Poland lags behind the European Union in activities aimed at transforming the power sector into an economic sector that do not threaten the climate. The delay is mainly in the slow transition from hard coal and lignite as the leading energy carriers and, consequently, in the slow implementation of solutions based on RES, including the production of zero-emission hydrogen. This is indicated, among other things, by the results of the SWOT analysis.

The war in Ukraine and its impact on supplies and prices of fossil energy resources should motivate the Polish authorities to revolutionise their energy source strategy. It is not a matter of replacing coal, oil, or gas imported from Russia with energy resources imported from other geographical directions but of taking decisive steps to radically reduce dependence on these finite resources in favour of RES. The change in the strategy should be reflected in the efficient adoption of new legal regulations to reconstruct the Polish power sector. It is advisable that Poland opens up to the opportunities arising from support instruments offered by the European Union. The NECP2030, PEP2040, and PHS should be changed so that the planned restructuring activities and their time frames are in line with the European Green Deal.

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Appendix A

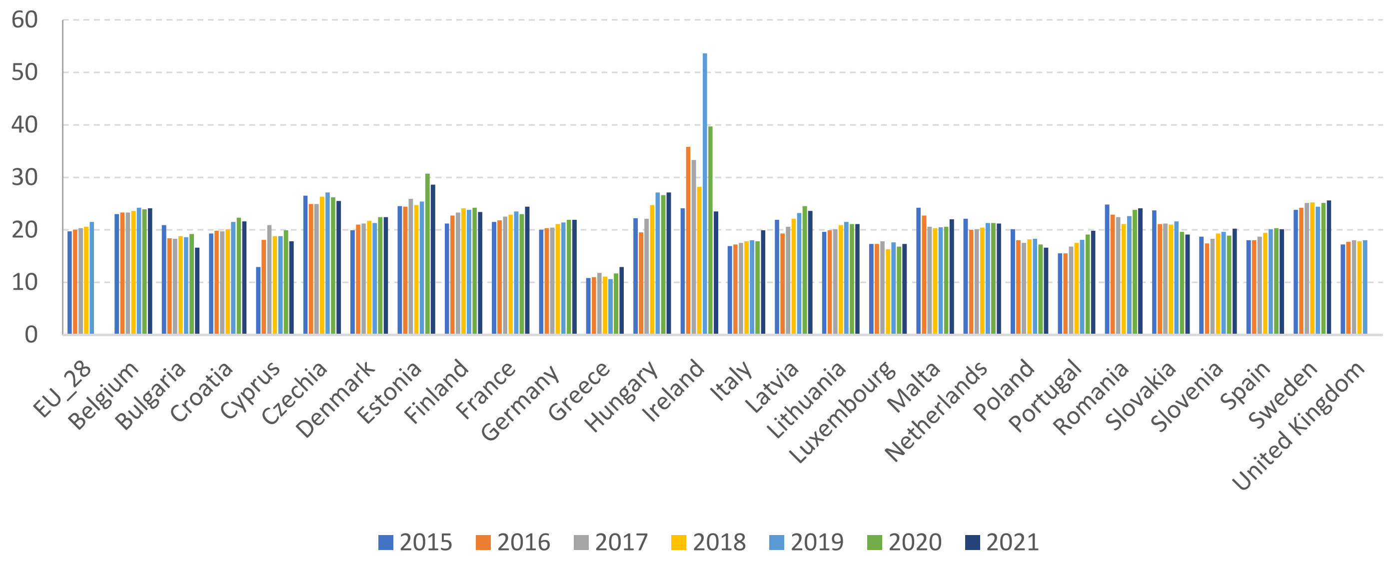

Figure A1. Gross fixed capital formation in relation to GDP in EU countries, 2015–2021. Source: own elaboration based on [45].

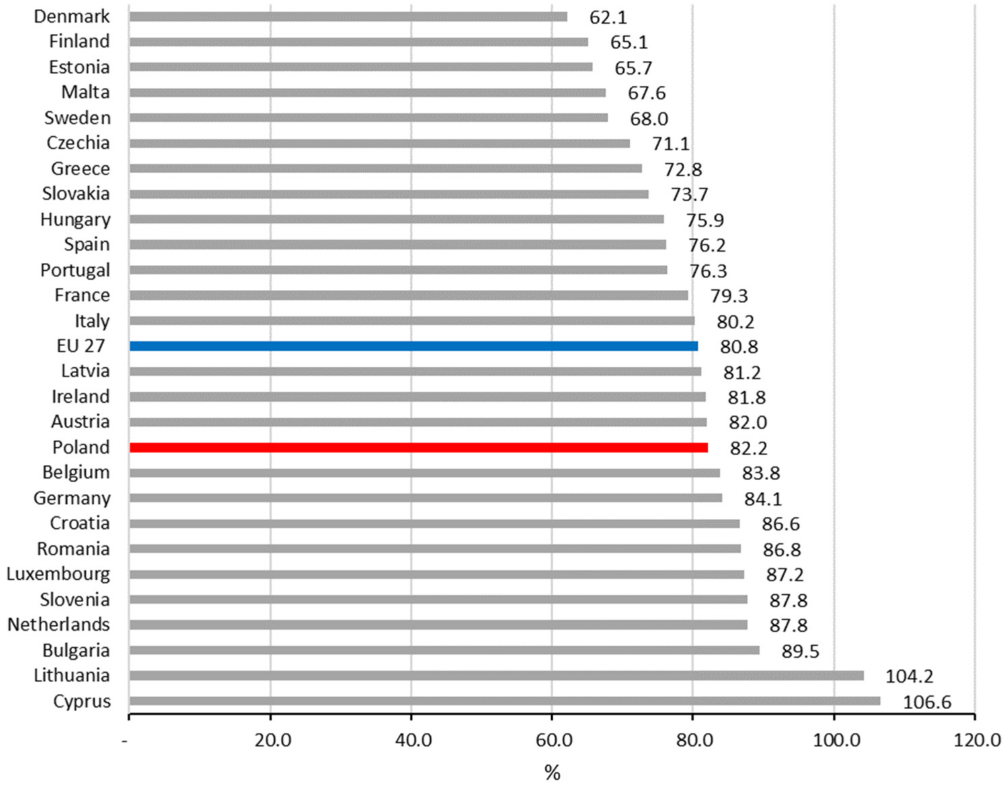

Figure A2. Greenhouse gas emissions intensity of energy consumption by EU27 country in 2020. Index, 2000 = 100. Source: own elaboration based on [27].

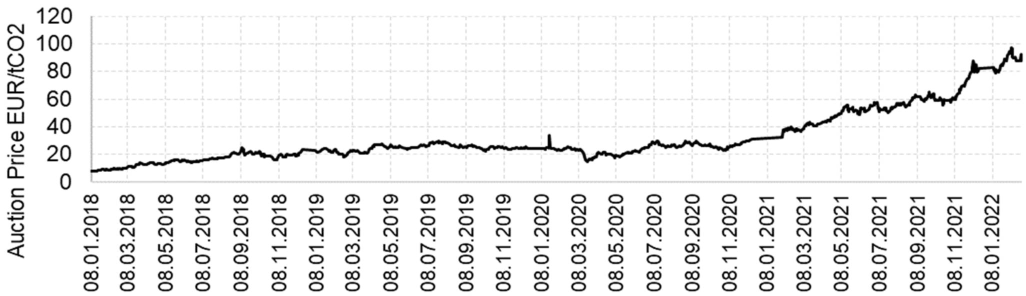

Figure A3. The market prices of CO_2 emission permit EUA (Carbon Emissions Allowances). Source: own elaboration based on [46].

Appendix B

Table A1. SWOT relationships between factors used in the analysis.

	O1	O2	O3	O4	T1	T2	T3	T4
S1	1	1	1	1	0	1	0	0
S2	1	1	1	1	0	1	0	1
S3	1	1	1	1	0	1	1	1
S4	0	1	1	0	0	0	1	1
W1	1	1	1	1	1	1	1	1
W2	0	1	1	1	1	1	1	1
W3	0	1	1	0	1	1	1	1
W4	0	1	1	0	1	1	1	1
W5	1	1	1	0	0	0	0	0

Source: own elaboration.

Table A2. TOWS relationships between factors used in the analysis.

	S1	S2	S3	S4	W1	W2	W3	W4	W5
O1	1	1	1	1	0	0	0	0	0
O2	1	0	1	1	1	1	1	1	0
O3	0	1	1	1	0	1	0	0	0
O4	1	1	1	1	1	1	1	0	1
T1	1	1	1	0	1	0	0	0	0
T2	0	0	0	1	0	0	0	0	0
T3	1	1	0	1	0	1	0	1	0
T4	0	0	0	1	1	0	0	0	0

Source: own elaboration.

Table A3. Collective results of SWOT/TOWS analysis.

	Results of SWOT		Results of TOWS		Summary of SWOT/TOWS	
Combination (Strategy)	**Sum of Interactions**	**Weighted Sum of Interactions**	**Sum of Interactions**	**Weighted Sum of Interactions**	**Sum of Interactions**	**Weighted Sum of Interactions**
S/O	14	6.8	14	7.1	28	13.9
S/T	8	3.15	8	4.5	16	7.65
W/O	14	6.2	9	3.85	23	10.05
W/T	16	7	4	1.8	20	8.8

Source: own elaboration.

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