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Is the Polish Solar-to-Hydrogen Pathway Green? A Carbon Footprint of AEM Electrolysis Hydrogen Based on an LCA

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Abstract: Efforts to direct the economies of many countries towards low-carbon economies are being made in order to reduce their impact on global climate change. Within this process, replacing fossil fuels with hydrogen will play an important role in the sectors where electrification is difficult or technically and economically ineffective. Hydrogen may also play a critical role in renewable energy storage processes. Thus, the global hydrogen demand is expected to rise more than five times by 2050, while in the European Union, a seven-fold rise in this field is expected. Apart from many technical and legislative barriers, the environmental impact of hydrogen production is a key issue, especially in the case of new and developing technologies. Focusing on the various pathways of hydrogen production, the essential problem is to evaluate the related emissions through GHG accounting, considering the life cycle of a plant in order to compare the technologies effectively. Anion exchange membrane (AEM) electrolysis is one of the newest technologies in this field, with no LCA studies covering its full operation. Thus, this study is focused on a calculation of the carbon footprint and economic indicators of a green hydrogen plant on the basis of a life cycle assessment, including the concept of a solar-to-hydrogen plant with AEM electrolyzers operating under Polish climate conditions. The authors set the range of the GWP indicators as 2.73–4.34 $kgCO_{2eq}$ for a plant using AEM electrolysis, which confirmed the relatively low emissivity of hydrogen from solar energy, also in relation to this innovative technology. The economic profitability of the investment depends on external subsidies, because, as developing technology, the AEM electrolysis of green hydrogen from photovoltaics is still uncompetitive in terms of its cost without this type of support.

Keywords: green hydrogen; solar-to-hydrogen; photovoltaic power plant; anion exchange membrane (AEM); life cycle assessment (LCA); carbon footprint

Citation: Pawłowski, A.; Żelazna, A.; Żak, J. Is the Polish Solar-to-Hydrogen Pathway Green? A Carbon Footprint of AEM Electrolysis Hydrogen Based on an LCA. *Energies* **2023**, *16*, 3702. https://doi.org/10.3390/en16093702

Academic Editors: Fabio Montagnaro and Roberto Solimene

Received: 29 March 2023
Revised: 21 April 2023
Accepted: 24 April 2023
Published: 26 April 2023

1. Introduction

Energy is the crucial factor for the sustainability of our society. The energy sector earns five trillion dollars every year, producing 3000 gigawatts annually [1]. Unfortunately, 80% of global final energy consumption is still from fossil fuels, which results in the pollution of the environment and important climate disturbances [2]. The burning of hydrocarbons is the main source of the most important greenhouse gas—carbon dioxide. The total emissions of CO_2 in 2021 amounted to 41,062,896,000.00 Mg [3]. This is why decarbonization is one of the major concerns for the future. Fighting climate change by reducing greenhouse gas emissions is one of the basic United Nations' Sustainable Development Goals. More than 100 countries have pledged to achieve carbon neutrality. In Europe, Norway will become carbon neutral by 2030, Finland and Sweden by 2045, and the European Union as a whole community by 2050, with the same goal for Great Britain. In Asia, both the Republic of Korea and China will achieve this goal by 2050 [4].

The most important part of achieving carbon neutrality is by supporting renewable sources of energy. This is another of the UN's Sustainable Development Goals. It has very strong support globally. Over the last few years, especially in the context of solar and wind energy, every year there has been a new record. Even in 2020, which involved full lockdowns and a global pandemic, records were achieved. In 2020, the global wind capacity was 774 GW (12.5% more than in 2019) and the global PV solar capacity was 760 GW (18% more than in 2019) [5]. In 2021, as much as 94 GW of new wind power plants and 175 GW of solar plant energy were created—a new record for the year [6].

However, the renewable sources of energy in many parts of the world are not stable enough because of changing weather conditions. Hydropower is supposed to be the most predictable source of renewable energy, but climate disruptions also bring threats to this source of energy [7].

An important alternative is nuclear power. However, there is uncertainty concerning its safety, especially after the Fukushima disaster. The world's largest nuclear power plant, Kashiwazaki-Kariwa, is also located in Japan, with a capacity of 7965 MW. During the tsunami of 2011, the facility was not affected; nevertheless, it shut down and more money was spent on better safety installations. The plant is still not in operation and its future is unknown [8]. However, nuclear power has been successful in many other regions, in France in Europe, in China and South Korea in Asia, and in the USA and Canada in America [9].

Another solution which is very promising is the use of hydrogen. In our opinion, this may be the fuel of the future, but still there are many problems that need to be solved. This paper presents the advantages and problems connected with the production of energy from hydrogen, the current legislation concerning hydrogen in the European Union, and a local case study from Poland, a country that belongs to this community.

1.1. Hydrogen as an Energetic Alternative

Hydrogen is the most common element in our environment, so there is no danger that its resources may be depleted. Huge resources are available in water, hydrocarbons (including biogas and methane), and also in organic matter. It is true that during a combustion reaction or a transformation within hydrogen-based electrochemical devices, no additional substances harmful to the environment are formed apart from neutral water. Hydrogen forms more compounds than any other element [10]. Hydrogen is also similar to alkali metals and halogens. It forms not only oxides, but also sulfides and halides. On a weight basis, hydrogen can deliver three times more energy than gasoline. What is more, when burning hydrogen, the amount of pollutants emitted into the atmosphere will be lower than that in the case of gasoline [11].

On the other hand, there are different ways of producing hydrogen, with varying and sometimes serious environmental consequences. Among these production technologies, thermochemical, photochemical, photocatalytic [12,13], photoelectrochemical, and biocatalytic processes may be distinguished [14].

The choice of hydrogen production methods depends, to a large extent, on the available resources and existing energy systems in individual countries, as well as on the pursued political goals, i.e., decarbonization and supporting economic growth, etc.

Different countries use a variety of terminology, adopting different assumptions and attitudes towards certain technologies. First of all, hydrogen has many different categorizations [15]. Increasingly, the multiplication of different shades of hydrogen has overcomplicated this discussion. There have been attempts to settle the color debate, with the aim of establishing clear definitions for the carbon content, technology, and sources of electricity that create them.

At the same time, in addition to color, more and more attention is being paid to carbon intensity or carbon equivalence. The intensity of carbon dioxide emissions—expressed as the Mgs of CO_2 per Mg of H_2 produced—is a technology-neutral criterion for assessing the hydrogen footprint [16]. There are four basic kinds of hydrogen: brown, grey, blue, and green (see Table 1).

Table 1. The color spectrum of hydrogen (own elaboration based on [16,17]).

Terminology		Technology	Energy Source	GHG
Production using electricity	Green	Electrolysis	RES	Minimal
	Pink		Nuclear power	
	Yellow		Grid electricity	High/Moderate
	Blue	Steam reforming + Carbon capture & storage	Natural gas, coal	Low
Production using fossil fuels	Turquoise	Pyrolysis	Natural gas	Moderate
	Grey	Steam reforming		
	Brown	Gasification	Lignite	High
	Black		Coal	

Gray hydrogen can be commercially produced on the base of fossil fuels in different ways:

- steam and/or oxygen hydrocarbon reforming, steam methane reformer (SMR),
- ATR: the autothermal reforming of natural gas,
- or through a partial oxidation of coal or heavy oil [18].

In all three cases, syngas (containing H and CO) is produced. The CO may be removed through a water displacement reaction in a gas exchange reaction. Through this, more hydrogen can be obtained, as can more CO_2. The present yearly production of gray hydrogen is 70 Mt (and 830 Mt of CO_2) [19]. At the same time, this is the cheapest technology.

Brown hydrogen—in this technology, coal is used and hydrogen is produced through coal gasification. This process is in use in many different industries. It is based on the conversion of carbon-rich substrates into hydrogen and is connected with important carbon dioxide emissions. The global production of brown hydrogen is around 79 Mt annually, but this also comes with emissions of 830 Mt of carbon dioxide—the highest amount for all kinds of hydrogen production [20].

Blue hydrogen technology is similar to that of gray hydrogen, but with blue hydrogen, some of the carbon dioxide released through the steam methane reformer process is captured. For the blue hydrogen facilities that are currently operating on a commercial basis, carbon capture occurs only in the steam methane reformer process and there is currently no attempt to capture the carbon dioxide resulting from the combustion of natural gas, which is used to provide heat and high pressure for process purposes. Carbon capture storage (CSS) requires energy, which is often provided by electrical power generated by the burning of additional natural gases [21].

Finally, with regard to green hydrogen, this is the technology chosen for our study, which is also strongly supported by the European Union and is presented in the next paragraph.

1.2. Green Hydrogen

Green hydrogen is produced via the process of water electrolysis, using only electricity from renewable energy sources. The electrolysis process can split water into hydrogen and oxygen molecules [22]. Electrolysis requires both water and electricity. About 9 L of water are needed to produce 1 kg of H_2, producing 8 kg of oxygen as a by-product, which can be used on a smaller scale in healthcare or on a larger scale for industrial purposes [23,24]. If all of today's hydrogen production, which is around 70 Mt of H_2, was to be produced by electrolysis, this would result in a water requirement of 617 million cubic meters, which is equivalent to 1.3% of the global energy sector's water use today, or roughly twice as much as the current water consumption for the hydrogen produced from a steam methane reformer.

Water electrolysis methods can be divided into three main types:

- alkaline,
- membrane (PEM—proton exchange membrane and AEM—anion exchange membrane),
- based on cells with solid oxides (SOE—solid oxide electrolyzer).

Table 2 summarizes the parameters of these typical water electrolysis methods.

Table 2. Basic parameters of alkaline electrolyzers, PEM, and SOE (own elaboration based on: [23]).

Specification [Unit]	Alkaline	PEM	SOE
Technological maturity	Market	Research and development	Research and development
Temperature of cell [°C]	60–80	50–80	900–1000
Pressure in cell [bar]	<30	<30	<30
Unit energy consumption [kWh/Nm^3]	4.5–7.0	4.5–7.5	2.5–3.5
Partial load [%]	20–40	0–10	-
Lifespan [yrs]	20–30	10–20	-
Hydrogen purity [%]	99.8	99.999	-
Boot time [min.]	15	<15	>60

Alkaline electrolysis systems are most often compared to other water electrolysis methods due to them having the longest presence in the market. Electrolysis based on solid oxide (SOE) systems is the most efficient in terms of its use of electricity, but it is still under development. Corrosion, seals, thermal cycling, and chromium migration are the main challenges facing this SOE technology [25].

Proton exchange membrane (PEM) electrolysis systems are more efficient than alkaline electrolyzers. Their corrosion and sealing problems are not as problematic as those in SOE cells, but the cost of membrane cells is still higher compared to alkaline cell systems [25].

Alkaline cell systems have the lowest capital cost and lowest efficiency, but the cost of the electricity used for their electrolysis is the highest [25].

Green hydrogen is considered to be a clean solution, since it is based on renewable energy [26]. However, due to its technological maturity level, it is also the most expensive solution. Therefore, the challenge is to efficiently produce hydrogen as a fuel when extracting it from the environment in the cheap way and without additional emissions of pollutants, such as carbon dioxide. The main obstacle in this case is the cost of production; however, it is still possible to introduce green hydrogen into the real world. The price is supposed to fall with further technological development and growing production, and financial incentives may lead to the economic efficiency of such an investment.

As of now, the country that has been most successful in introducing these hydrogen technologies is China—it is the largest user and producer of hydrogen in the world, with more than 24 million Mg of coal-based hydrogen per year. In the five-year plan for the years 2021–2025, hydrogen is one of the main industries of the future for this country [27].

The European Union wants to follow this path, but there, green hydrogen is in focus.

However, among the most important factors regarding hydrogen production is not only technology, but also policy.

1.3. Policy Supporting Hydrogen Production in the European Union

Until 2017, only one country, Japan, had a national hydrogen strategy. Currently, over 30 countries have developed or are preparing hydrogen strategies, which indicates a growing interest in the development of clean, green energy solutions.

The development of the hydrogen market in Europe is connected to the implementation of the European Union's current climate policy.

It is worth mentioning the EU's AFID—Alternative Fuels Infrastructure Directive of 22 October 2014. It obliges the member states to create an appropriate number of hydrogen fueling stations by the end of 2025. However, this number is not given precisely and is ultimately intended to result directly from the policy adopted by each member state [28].

The widest approach was presented in the document of the European Commission entitled the European Green Deal. Its main goal is the climate neutrality of the EU by 2050. The main goal is to achieve climate neutrality by 2050 [29]. The directions of changes for individual sectors of the economy are as follows:

- the decarbonization of the gas sector by introducing low-emission gases such as hydrogen,
- support for clean technologies in industry, including clean hydrogen and energy storage,

- the decarbonization of transport (air, road, rail, and water), i.e., by introducing alternative, sustainable transport fuels [29].

In 2020, a hydrogen strategy for a climate-neutral Europe was issued [30]. It may be summarized in five points:

- investment support,
- support production and demand,
- creating a hydrogen market and infrastructure,
- research and cooperation,
- international cooperation.

This was enhanced in 2021 as the "Hydrogen and gas markets decarbonisation package proposal". It was connected with the Regulation of the European Parliament and of the Council on the internal markets for renewable and natural gases and hydrogen [31], and the Directive of the European Parliament and the Council on the common rules for the internal markets and natural gases and hydrogen [32]. According to this package:

- hydrogen infrastructure should gradually complement the natural gas network,
- a fossil gas infrastructure should gradually be replaced by other sources of methane, and fossil gas must be replaced with low carbon gases, such as hydrogen [32].

In May 2022, a new plan called "REPowerEU" was introduced, in order to rapidly reduce the dependence on Russian fossil fuels and fast forward the green transition. The community assumed a cut-down of two thirds of Russian gas import by the end of 2022, and all imports should be stopped by 2027.

There are three pillars of this plan:

- a demand reduction (energy savings and a better energy efficiency),
- a diversification of the suppliers for conventional (fossil) fuel imports and a further reduction in greenhouse gas emissions,
- an acceleration of the transition to renewable energy sources: 45% of energy from renewables in 2030 [33].

The strategy also includes many more detailed goals, like doubling the EU's production of biomethane and investments into hydrogen technologies, especially ports and storage facilities. For example, in the Mediterranean and North Sea, major hydrogen corridors will be developed [34].

Delivering the REPowerEU objectives requires an additional investment of EUR 210 billion between now and 2027 [33].

Despite these ambitious goals, in 2022, the overall hydrogen consumption in the EU was only about 2% of the energy market [34]. It was used mainly for the production of different kinds of plastics and fertilizers. Unfortunately, 96% of this production was based on natural gas, which meant important emissions of carbon dioxide. However, this will change. The European Commission has proposed the production of 10 million Mg of renewable hydrogen by 2030 and the importing of 10 million Mg by 2030. What is more, the EU strategy assumes a phased approach to the full development, production, and dissemination of green hydrogen; 40 GW of green hydrogen based on electrolysis is planned to be installed by 2030. During the transitional period, the EC enables the production of hydrogen using, e.g., fossil fuels combined with carbon capture and storage (CCS) technology. Gradually, renewable hydrogen will become cost competitive in relation to other types of hydrogen. After 2050, only green-emission-free hydrogen will be allowed in the EU. The costs associated with the comprehensive development of green hydrogen are around EUR 180–EUR 470 billion [29].

All countries in the EU, including Poland—the country where the case study installation is located—must also implement this European energy and climate policy. However, they also have their own legislation.

In the case of Poland, new directions for the energy sector were introduced by the Energy Policy of Poland until 2040 [35], which was adopted in 2021 by the Council of

Ministers (2021). This document takes into account the objectives announced by the European Commission in 2019 and the principles of the European Green Deal.

The climate neutrality of Poland will require an energy transformation, which needs the building of a zero-emission energy system.

It is important to assume that the energy transformation process will involve the emergence of new participating industries in the transformation of the energy sector, a vital part of which is the development of low-emission transport [35].

The PEP2040 strategy also relates to hydrogen in the following ways:

- a fuel alternative to crude oil for transport,
- a tool for industry decarbonization,
- support for increasing the share of renewable energy sources,
- support for the decarbonization of the gas sector by 2030 [35].

For the transport and distribution of the produced quantities of hydrogen, the existing gas infrastructure may be used. By 2030, the Polish gas network will be able to transport a mixture containing approximately 10% of biomethane or green hydrogen [35].

A domestic hydrogen production of over 1 million Mg annually places Poland in third place in Europe, but this is not hydrogen produced using renewable energy sources, so it cannot be included in the energy transformation leading to climate neutrality [35].

The general objective included in the PSW project is therefore to transform the Polish hydrogen industry in order to achieve climate neutrality and further economic development.

This is a strategic challenge for the authorities and the national economy, which requires a comprehensive approach that takes into account the entire value chain and solves a wide range of problems. In all cases, green hydrogen is intended to minimize the use of fossil fuels, thus reducing the greenhouse gas emissions into the atmosphere [35].

1.4. Research Problem of the Study

Apart from the legislation and infrastructure problems, there are a lack of data on the environmental impact in relation to the hydrogen production in Poland, especially in the case of new and developing technologies. Previous studies related to hydrogen production have focused mostly on mature hydrogen production technologies [36], including electrolysis [37]. There has only been one paper (preprint) published on the life cycle assessment of an AEM electrolyzer [38]; however, it does not cover the full pathway of hydrogen production, focusing on the optimization of its construction. Therefore, the aim of this study is calculation of the carbon footprint of a green hydrogen plant on the basis of a life cycle assessment, including the concept of a solar-to-hydrogen plant with AEM electrolyzers operating under temperate climate conditions.

The object of this study is the concept of a green hydrogen plant with 5 MW peak power located in Zarzecze, in the southern part of the country. This is going to be one of the first green hydrogen plants in Poland. The novelty of this study is connected to the application of the newly developed anion exchange membrane (AEM) technology for electrolysis. Therefore, the results of the life cycle assessment presented in the article are the primary raw data results connected to this issue and can be used for further studies estimating green hydrogen potential, as well as the carbon dioxide emissions related to the solar-to-hydrogen pathway.

2. Materials and Methods

The object of this study is a photovoltaic power plant (5 MWp) located in Zarzecze (the Podkarpackie Voivodship with higher solar resources compared to most of the Polish territory, with an average annual insolation of 1100 kWh·m^{-2}), designed with the use of an electricity storage system in order to provide an efficient energy supply system for a hydrogen generator. The conceptual analysis of the designed green hydrogen plant, annually providing about 80 Mg of industrial-purity hydrogen (99.8%), was based on several premises. Initially, the technology of the power generation was chosen as bifacial mono crystalline modules. Two basic variants of the possible design (ground-mounted, as well as a one-dimension tracker) were analyzed and marked as "PV standing" and "PV tracker" in a further study. The simulation of the energy yield of the installation, based on the standing and tracker solution, was carried out with the ArcheliosPro software, enabling the calculation of large PV plants. The installation on a tracker generated a significantly higher yield for the same installed power, minus the expenditure on the actuators. The condition negatively affecting this type of solution was the increased demand for the installation area.

During the design, a technological analysis was included, and AEM technology for electrolysis was selected for the application, due to the relatively low cost of its operation and its good correlation with the changing power supply. In terms of the life cycle assessment, the technological scheme of the designed green hydrogen plant, supplied by a photovoltaic power plant of 5 MW_p, is presented in Figure 1. Appendix A contains more details on the solutions used in the life cycle inventory stage.

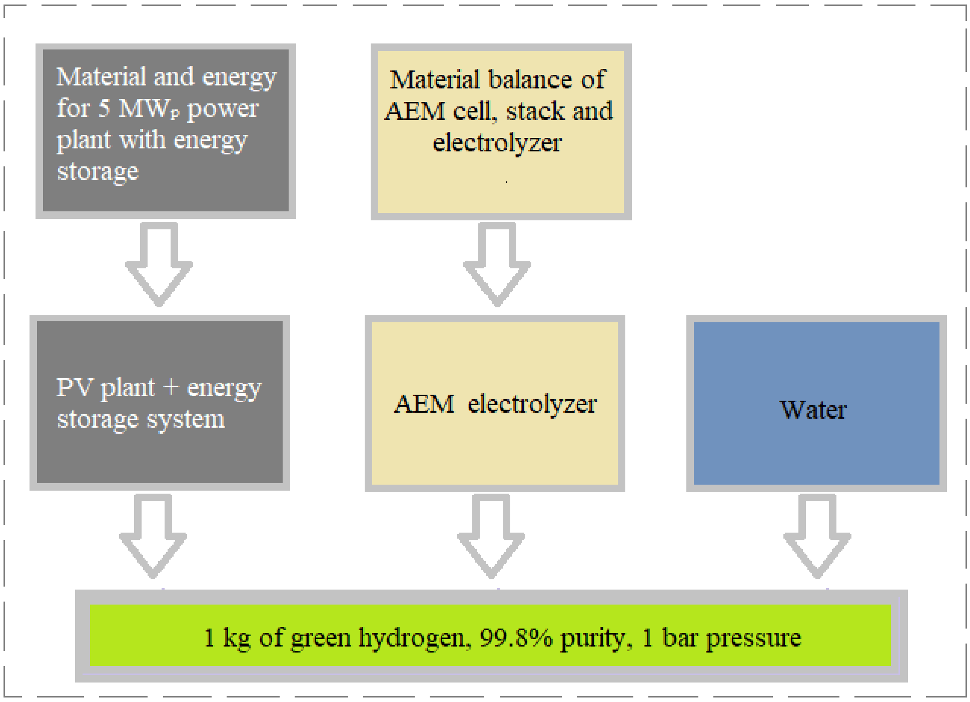

Figure 1. System boundaries for green hydrogen generation.

The basic element of the system was the 5 MW_p photovoltaic power plant based on monocrystalline bifacial modules (technical characteristics in Table 3). The plan was to use a power substation adapted to the required voltage range, equipped with two transformers with a maximum power of 2500 kVA each. The low-voltage switchgear should be adapted to connect 34 inverters, 17 for each section of the station. The PV power plant LCA model was extrapolated from Ecoinvent database processes, assuming that the efficiency of the modules changed from 18% to 21.54%, which affected the material and energy balance of the system.

Table 3. Characteristics of the modeled PV panel.

Parameter [Unit]	Front Side	Back Side
Rated power STC [W]	670	469
Open circuit voltage [V]	44.3	44.0
Short circuit current [A]	19.24	13.56
Maximum voltage for rated power [V]	37.22	37.21
Maximum current for rated power [A]	18.01	12.61
Module efficiency [%]	21.57	

In order to use the surplus of electricity generation in the photovoltaic generators, storage based on chemical cells was planned. A typical Li-ion solution with a power of 500 kW and a capacity of 7470 kWh was adopted. The time perspective for the balancing of the examined systems was 30-year lifespan, which is typical for an LCA of PV systems [39]. During the mentioned period, the batteries and inverters need to be replaced every 15 years, based on the producers' and literature data [40].

As an electrolysis technology, anion exchange membrane cells were selected due to their low requirements of purity (industrial processes), as well as their low investment and operation costs. The technical parameters of the selected AEM electrolyzer are included in Table 4, while four single devices were chosen, each with 1.25 MW of power. Due to the conceptual stage of the project, additional processes, such as further H_2 compression, storage, and disposal, as well as oxygen disposal, were not included in the life cycle inventory.

Table 4. Characteristics of the modeled AEM electrolyzer.

Parameter [Unit]	Value
Net production [Nm^3/h]	210
Range of production changes [%]	3–105
Power consumption of the set [kWh/Nm^3]	4.8
Hydrogen purity [%]	99.8
Outlet pressure [bar]	up to 35
System installation area [m^2]	30
Water demand [dm^3/Nm^3]	2

The collected data were furthermore used for a comparative analysis of the PV generator configurations, as well as a calculation of the carbon dioxide emissions. The CO_2 was balanced via the Intergovernmental Panel on Climate Change: Global Warning Potential 100 [41], on the basis of a life cycle assessment, according to ISO 14040 and using SimaPro v. 8.0.5.13 (PRé Consultants B.V., Amersfoort, The Netherlands) with the Ecoinvent v3 database.

A life cycle assessment is a frequently used method supporting the calculation of the possible environmental problems related to the object of a study. LCAs are based on comprehensive energy and mass balances, by means of data on the environmental effects in the context of the selected impact categories. One of the main issues is the proper life cycle inventory stage. In this study, the life cycle inventory was based on the detailed scheme of the systems, as well as the energy balance, while the end of life processes were omitted because of a lack of data. The functional unit for the final analysis was 1 kg of the produced H_2 (a purity of 99.8%), while several internal units were used in the balancing of the materials and energy necessary to build the photovoltaic power plant, energy storage system, and electrolyzer (see Appendix A).

Due to the requirements of the life cycle assessment, the AEM cells had to be characterized in detail, as the new and developing technology. The material balance of the AEM cells can be found in [38], while additional data, including the lifetime of the technologies used and the photovoltaic system balances, can be found in [39,40]. It was assumed that the lifetime of the photovoltaic technology was 30 years, while the AEM electrolyzers should be replaced in this period because of their shorter operation period (assumed to be 15 years in this study). However, accurate modeling of the AEM balance of the plant is difficult due to a lack of data. More exact modeling will be possible when the specific data on its components are published.

The life cycle impact assessment included Global Warming Potential (IPCC GWP 100a) indicators [41]. As an extension, the economic feasibility of the investment was calculated by the mean of the Net Present value and Payback Period methods [42]. In order to evaluate the plant as a solution typical for the construction of near-existing plants processing the product, a solution based on direct hydrogen distribution and the release of oxygen into the atmosphere was adopted for the valuation on an ongoing basis. For all the scenarios, simplified simulations were assumed, which did not assume changes in the fixed costs, changes in the product prices, or required capital expenditures in the modernization and repair of the infrastructure.

3. Results and Discussion

The results of the LCA study were presented as raw data, as well as in relation to the main functional unit. This allowed for the following of the main unit processes responsible for the carbon dioxide emissions, as well as a calculation of the total GHG emissions of the unit hydrogen production.

3.1. Results of Global Warming Potential Calculation

The results presented in Figure 2 were calculated for 1 kWh of the electricity generated and stored in the PV power plant, with Li-ion batteries in the case of the "PV plant + storage". The "AEM electrolysis" process included materials and energy for an electrolyzer construction, assuming its lifetime to be 15 years. "Water" included 2 dm^3 of deionized water per 1 Nm^3 of H_2 generated by the AEM electrolyzer.

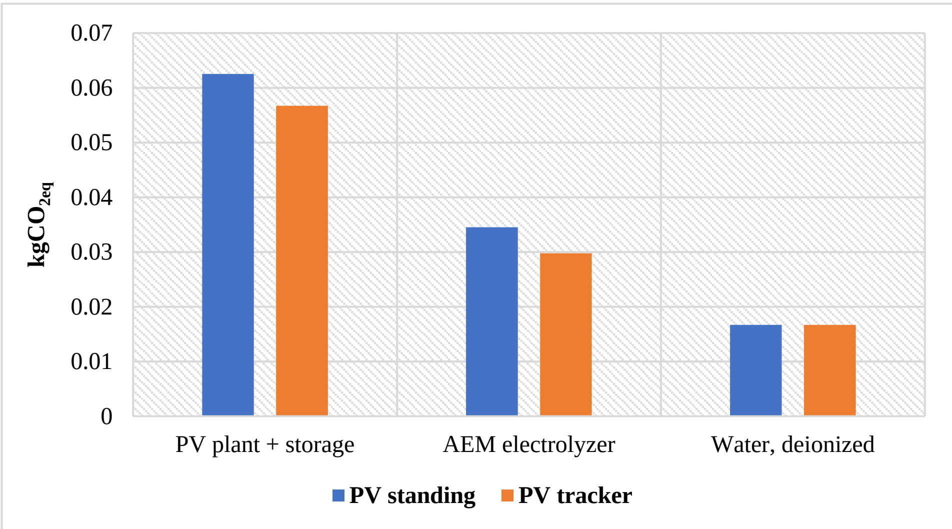

Figure 2. Results of carbon dioxide emission calculation for: 1 kWh of energy generated by PV plant/storage system; and 1 kg of produced hydrogen (by AEM stack and water consumption).

It was found that 56.34 kWh of energy was used to produce 1 kg of hydrogen under normal conditions. The presented results justified the selection of the PV plant on the tracker, since there was a high effect on the efficiency of the electricity generation (4,491,189 kWh of yearly production vs. 3,902,968 kWh for PV standing system), which affected both the PV-plant-related emissions, as well as the hydrogen output of the AEM electrolyzer. This relation is more clearly presented in Table 5. However, it has to be mentioned that the lifetime of both systems was assumed to be the same, and no additional servicing of the moving elements of the tracker was included.

Table 5. Results of GWP100a calculation for 1 kg of produced hydrogen.

GWP, $kgCO_{2eq}$	PV Standing	PV Tracker
max *	4.34	3.85
min *	3.01	2.73
mean	3.57	3.24

* min and max values calculated on the basis of Monte Carlo analysis including 95% confidence interval.

As it can be easily noticed in Figure 3, most of the carbon footprint related to the green hydrogen production was connected to electricity generation. This confirmed the previous LCA results for the solar-to-hydrogen pathway in relation to other electrolysis technologies, where the share of a PV generator in the total carbon dioxide emissions was estimated to be between 88 and 99% [43]. The interpretation of the results obtained in this study should be placed in the broader context of the previous literature studies, which inform about carbon footprints exceeding 20 kg of CO_2 per 1 kg of hydrogen in the case of the world average electricity production (and even more for coal-based electricity generation), as presented in Table 6. The obtained results confirm those of similar studies in this area, which rank green hydrogen at the forefront of low-emission technologies.

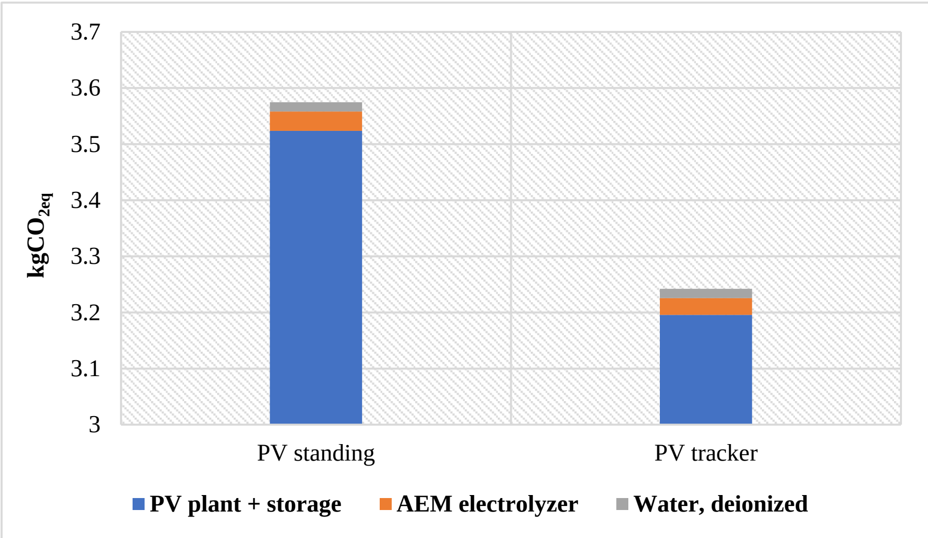

Figure 3. Results of carbon dioxide emission calculation for functional unit (1 kg of produced hydrogen).

Table 6. Carbon footprint of selected methods of hydrogen production ($kgCO_2$ per 1 kg of H_2).

Means of Production	High	Low	2020	Source
Coal Gasification	25.31	14.40	19.14	[44]
Steam Methane Reforming	15.86	10.72	12.4	
Green—wind	2.20	0.80	1.34	
Green—solar	7.10	1.99	3.74	
Green—assumed 50/50 split	4.65	1.40	2.54	[45]
Green—biogas reforming	7.99	0.23	3.61	[43]
Blue	12.70	2.70	8.04	[46]
Electricity (coal)	-	-	21.82	[47]
Current study (solar, Poland)	3.85	2.73	3.24	Own calculation

As can be stated on the basis of the results obtained in this study, in relation to the previous literature analysis (Table 6), the wind-to-hydrogen pathway seems to be the most effective for carbon footprint reduction, while solar-to-hydrogen technology remains in the second most effective position. It is worth emphasizing that carbon dioxide emissions related to green hydrogen production via AEM electrolysis, as well as other electrolysis technologies [43] in various locations [48], are still significantly lower compared to traditional technologies using a conventional grid electricity mix or fossil fuel feedstocks.

3.2. Results of the Calculation of Economic Indicators

The appropriateness of the construction of the installation is determined by calculating the NPV coefficient. For the annual base case impact, the value of the hydrogen produced is determined. The annual income from the hydrogen production is assumed to be PLN

1,862,132.76, 396,198.5 EUR, assuming a price of USD 4.7 per kilogram of hydrogen and a dollar at the exchange rate of PLN 4.97; EUR/PLN 4.7.

Scenario 1: An investment covered with own funds—only hydrogen was utilized.

This scenario assumed that the project would be financed only with own funds. The distributed good was hydrogen. The data were adopted on the basis of a statement of the investment and fixed costs, as presented in Table 7. The adopted period of 30 years for considering these investments was only to illustrate certain aspects; the real maximum time for considering such investments was 20 years.

Table 7. Calculation of economic indicators for Scenario 1.

Parameter [Unit]	Value
Net capital expenditure [EUR]	13,087,383
Annual net operating costs [EUR]	7184.47
Annual administration and staff costs [EUR]	58,212.77
Annual revenues from energy production [EUR]	396,198.5
Investment consideration period [years]	30
Discount rate [%]	6.50
Net Present Value [EUR]	−9,356,166.74
Payback Period [years]	29

Scenario 2: An investment co-financed with an 85% subsidy—only hydrogen was utilized.

This scenario assumed that the project would be financed with own funds supported by an 85% subsidy from external sources, as presented in Table 8. A hydrogen-only distribution was included.

Table 8. Calculation of economic indicators for Scenario 2.

Parameter [Unit]	Value
Net capital expenditure [EUR]	1,963,107
Annual net operating costs [EUR]	71,846.6
Annual administration and staff costs [EUR]	58,212.77
Annual revenues from energy production [EUR]	396,198.5
Investment consideration period [years]	30
Discount rate [%]	6.5
Net Present Value [EUR]	1,089,162.23
Payback Period [years]	8

As it can be noticed, the second option was the preferred one, since both the NPV and PP indicators showed that the investment was justified in relation to the expected benefits and necessary expenditures. Although the technology of AEM electrolysis can be treated as one of the cheapest, its total investment costs are strongly related to the PV plant's facilities, the balance of the system, and the energy storage. This shows that the technology is not market mature enough to be economically effective without additional subsidies, which is also the common conclusion in this area based on the literature studies [48].

4. Conclusions

Hydrogen is treated as the future of the energy sector. However, considering the literature review, it should be mentioned that the methods of its production differ in many aspects, including their market maturity, price, and related emissions. For a carbon neutral economy, among others, green hydrogen will be promoted and economically supported. It also needs legislation, which, so far, is most developed in the European Union.

The results of the life cycle assessment of the solar-to-hydrogen pathway presented in the study led to the following conclusions:

- It can be justified to use renewable energy for hydrogen production in terms of minimizing greenhouse gas emissions. The study based on the conceptual design of a new green hydrogen power plant, including the newest technologies available, showed an acceptable level of carbon dioxide emissions when compared to the literature references.

- It is necessary to underline the effect of energetic efficiency on the final results of the LCA, since both the PV-related and AEM-related emissions were dependent on the amount of energy stored in the hydrogen. Thus, further technological development resulting in more efficient technologies will lead to a minimization of the environmental impact of hydrogen production.

The main limitation of the study is the fact that the present analysis relates to hydrogen under the pressure of 1 bar. In future studies, the authors are planning to broaden the scope of the analysis to also include the compression, transportation, and storage of hydrogen. The main problem is the unavailability of raw data, which will be solved when the power plant is put into operation. This will enable the analysis to be much more detailed.

It is also crucial to note that, as of now, the economic efficiency of investments cannot be obtained without external financing from supporting funds. This is why the future of hydrogen is connected not only with technical improvements that lower its impact on the environment, but also how to make such technologies cheaper through an entire life cycle assessment. This is a challenge which must be met in the near future. This is also a wide research area which must be fulfilled by many following studies.

Author Contributions: Conceptualization, A.Ż., A.P. and J.Ż.; methodology, A.Ż. and J.Ż.; software, A.Ż. and J.Ż.; validation, A.P.; formal analysis, A.P.; investigation, J.Ż. and A.Ż.; writing—original draft preparation, A.P. and A.Ż.; writing—review and editing, A.P.; visualization, A.Ż. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by FD-20/IS-6/042 granted by Faculty of Environmental Engineering, Lublin University of Technology.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Life Cycle Inventories of system elements.

Table A1. Life Cycle Inventory of PV power plant with energy storage system (own elaboration based on modified Ecoinvent database processes [49] and material/energy balance of designed power plant).

Component	Materials/Assemblies	Unit	Amount
Photovoltaic power plant	Photovoltaic plant, electric installation	p *	1
	Inverter, 500 kW	p	10
	Photovoltaic panels, single-Si bifacial, 5 MWp	p	1
	Photovoltaic mounting system, for 5 MWp open ground module	p	1
Energy storage system	Battery, Li-ion, rechargeable, prismatic	kg	57.9
Tracker	Single axis tracker, for 5 MWp PV installation	p	1

* p—piece.

Table A2. Life Cycle Inventory of AEM elecrolyzer (own elaboration based on [38,50] and material/energy balance of designed hydrogen generator with capacity 71.58 kg/h).

Component	Materials/Assemblies	Unit	Amount
Bipolar plate	Steel, chromium steel 18/8	kg	6661.67
Gasket	Tetrafluoroethylene	kg	0.12
Anode	Iron(III) phosphate	kg	17.36
	Anionic resin	kg	2.08
	Nickel, 99.5%	kg	93.73
Membrane	Anionic resin	kg	10.80
Cathode	Platinum	kg	0.09
	Rhuten	kg	0.04
	Carbon black	kg	1.17
	Anionic resin	kg	0.04
	Carbon black	kg	32.25
	Processes		
Nickel foaming	Metal working	kg	93.73
Inputs	Operating resources/kg H_2		
	Electricity	kWh	56.34
	Water, deionised	kg	10.62

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