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Article

Strategic Model for Yellow Hydrogen Production Using the Metalog Family of Probability Distributions

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Abstract: Storing energy in hydrogen has been recognized by scientists as one of the most effective ways of storing energy for many reasons. The first of these reasons is the availability of technology for producing hydrogen from water using electrolytic methods. Another aspect is the availability of relatively cheap energy from renewable energy sources. Moreover, you can count on the availability of large amounts of this energy. The aim of this article is to support the decision-making processes related to the production of yellow hydrogen using a strategic model which exploits the metalog family of probability distributions. This model allows us to calculate, with accuracy regarding the probability distribution, the amount of energy produced by photovoltaic systems with a specific peak power. Using the model in question, it is possible to calculate the expected amount of electricity produced daily from the photovoltaic system and the corresponding amount of yellow hydrogen produced. Such a strategic model may be appropriate for renewable energy developers who build photovoltaic systems intended specifically for the production of yellow and green hydrogen. Based on our model, they can estimate the size of the photovoltaic system needed to produce the assumed hydrogen volume. The strategic model can also be adopted by producers of green and yellow hydrogen. Due to precise calculations, up to the probability distribution, the model allows us to calculate the probability of providing the required energy from a specific part of the energy mix.

Keywords: renewable energy sources; hydrogen electrolyzer; yellow hydrogen; metalog; artificial intelligence

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1. Introduction

Currently, the energy market is undergoing a huge transformation, and this applies to both the energy producing sector [1–3] and its recipients. The demand for energy is constantly growing despite the existing modern and energy-saving energy receivers. For example, several trends in electricity consumption in the agricultural sector were highlighted in [4,5]. A very large share in energy consumption falls on the transport sector [6,7], which is also in competition for energy carriers and new fuels in order to meet the increasingly stringent emission standards. This is especially visible in the increasing number of hybrid and fully electric battery vehicles sold. This tendency is also confirmed by numerous studies in this area [8–17]. Despite the development of electromobility, alternative fuels for internal combustion engines are being developed simultaneously. In this area, there is a particular development of gas fuels, e.g., LPG, CNG, LNG, [18–22], biofuels [23,24], biodiesel [25–28], hydrogenated vegetable oil (HVO) [29–31], and various fuel mixtures for combustion in piston engines [32–35], alongside the research on fuel cells [36]. Very intensive work is also underway in the area of using hydrogen as an energy carrier in vehicles [37–40].

Storing energy in hydrogen has been recognized by scientists as one of the most effective ways of storing energy in many respects [41]. The first of these reasons is the availability of technology for producing hydrogen from water using electrolytic methods [42]. Currently, the market offers electrolyzers with alkaline technology [13,43–45], PEM [46–50], AEM [51,52], and SOE [53–55]. Another aspect is the availability of relatively cheap energy from renewable energy sources (RES) [56]. Moreover, one can count on the availability of large amounts of this energy [57,58]. At the level of market products, there are already proven technologies designed for the compression and storage of large amounts of hydrogen [59,60]. Moreover, hydrogen can be transmitted through pipelines and transported using the so-called pipeline trucks. In the area of technologies using hydrogen, many industrial processes should be mentioned, such as the production of artificial fertilizers, industrial chemicals, and steel. It is also worth considering chemical methods of storing hydrogen. Ammonia borane (AB) is widely considered to be a safe and efficient medium for H_2 storage and release [61,62]. Moreover, hydrogen can be a very good driving fuel for hydrogen fuel cell vehicles. Due to the simultaneous production of electricity and heat, hydrogen fuel cells can also be used to supply electricity and heat to residential and institutional buildings [45]. For now, fuel cells were only used as an emergency power supply for the latter in the event of a lack of electricity in the power grid. However, the availability of cheap yellow and green hydrogen may completely change the nature of the operations of large chemical companies and also affect the widespread use of hydrogen as a fuel in transport and as a fuel used to supply buildings with electricity and heat [63].

Colors are very often used to describe the origin of hydrogen. For example, very large amounts of gray hydrogen are currently produced in the world [64]. It is hydrogen produced in the process of the steam reforming of natural gas [65]. Therefore, it is a technology that uses fossil fuel and contributes to large emissions of carbon dioxide into the atmosphere. If the producer uses carbon dioxide capture technology at the level of gray hydrogen production, such a hydrogen will be called blue hydrogen. The most commonly used carbon dioxide capture technologies are CCS (carbon capture storage) and CCU (carbon capture utilization). Green hydrogen is the most desirable color of hydrogen [66,67]. It is produced in water electrolysis processes using energy coming exclusively from renewable energy sources [68–71]. Therefore, it can not only be obtained from photovoltaic systems but also from wind farms. Recently, yellow hydrogen has also been encountered. It is also produced by electrolytic methods and the energy for its production comes exclusively from solar photovoltaic systems [72]. In this article, the focus is yellow hydrogen. It can be produced in many different ways. In addition to water electrolysis, scientists are working on hydrogen production using photoreforming and plasma thermophotocatalysis methods [73,74]. In paper [75], the authors present the control platform architecture of a real hydrogen-based energy production, storage, and re-electrification system paired to a wind farm located in north Norway and connected to the main grid. This is one of the few green hydrogen production and storage systems that has been well described and researched.

Arcos et al. [76] presented evidence that hydrogen has become the most promising energy carrier for the future. The spotlight is now on green hydrogen, produced via water electrolysis powered exclusively by renewable energy sources. However, several other technologies and sources are available or under development to satisfy the current and future hydrogen demand [77]. The research presented in [78] clearly proves that yellow hydrogen is not yet competitive with fossil alternatives and needs incentive mechanisms for the time being. The paper [79] presents a review of the current and developing technologies used to produce hydrogen from fossil fuels and alternative resources like water and biomass. Many countries around the world have high sunlight, which favors the production of yellow hydrogen at low prices. According to scientists from Austria, at the moment, green hydrogen accounts for the most abundant hydrogen produced, while yellow hydrogen has little impact [80]. According to the authors, the importance of yellow hydrogen production will increase with the development of electrolyzers that will be able to operate at various load values. The second technologies supporting the production of yellow hydrogen are increasingly cheaper and more durable stationary storage facilities in the form of lithium-ion batteries. A paper published by Panić et al. provides an overview of color-based hydrogen classification as one of the main methods for describing hydrogen types based on currently available production technologies, as well as the principles and safety aspects of hydrogen storage [81]. However, this should be conducted with careful regard paid to the fact that many of the current hydrogen production technologies still need to increase their technological readiness level before they can become viable options [82,83]. Yellow hydrogen is an important type of low-emission hydrogen included in the European Hydrogen Strategy [84] and the national policies of individual countries [85,86]. Many scientists present different scenarios for the production of green and yellow hydrogen in different countries, such as Poland [87,88], Brazil [89], Spain [90], Austria [91], and other European countries [82]. They take into account the geographical context related to the amount of energy produced from the sun and legal aspects favoring the connection of new renewable-energy-generating capacity to the energy grid. Paper [92] proves that advancement in the PV industry and additional savings in the electrolyzer's electrical demand can further decrease the carbon footprint of yellow hydrogen. Produced from solar energy, yellow hydrogen can form the basis for the distributed production of smaller amounts of hydrogen needed to power individual hydrogen vehicles [93]. Photovoltaic systems placed on the roofs of houses, supported by energy storage, can provide enough energy to produce hydrogen to power several hydrogen vehicles. Large fleets of hydrogen vehicles and buses already require large amounts of energy, which will be a mix of renewable energy and will be delivered to the hydrogen producer via the power grid [94,95].

The demand of the Polish industry for large amounts of ecological hydrogen is huge [96]. It is enough to take into account the amounts of hydrogen produced in only two industries: petrochemicals and artificial fertilizers [97]. These two large groups of companies are currently undergoing a climate and energy transition and are gradually replacing gray hydrogen with its greener counterparts [98].

To produce large amounts of hydrogen, large amounts of energy are needed [99]. To produce 1 kg of hydrogen, 9 L of water and approximately 50 kWh of electricity are required. A big challenge related to building a hydrogen economy is to determine the actual demand for hydrogen and to provide the required amount of energy for its production in a timely manner. Only then are the subsequent links in the logistics chain activated, which are related to the charging, storage, transport, and refueling of hydrogen [100]. The aim of the article is to support the decision-making processes related to the production of yellow hydrogen using a strategic model which applies the metalog family of probability distributions [101]. The model allows its users to calculate, with accuracy regarding the probability distribution, the amount of energy produced by photovoltaic systems with a specific peak power. Therefore, using the model in question, it is possible to calculate the expected amount of electricity produced per day from the photovoltaic system and the corresponding amount of yellow hydrogen produced. Such a strategic model may be very useful for renewable energy developers who build photovoltaic systems intended specifically for the production of yellow and green hydrogen. Based on the model, they can estimate the size of the photovoltaic system needed to produce the assumed hydrogen volume. The strategic model can also be used by producers of green and yellow hydrogen. Due to the precise calculations, up to the probability distribution, the model allows us to calculate the probability of providing the required energy from a specific part of the energy mix. Due to the variability of the energy produced during the day/night cycle and the seasonality in the summer/winter cycles, hydrogen cannot be produced just by using the green energy from the sun [102]. The required energy must be supplemented by the energy from the wind, which also blows at night, i.e., when the sun is not shining [103]. The most stable of the renewable energy sources are hydroelectric power plants. Typically, however, the energy employed for hydrogen production is a mix [104]. To avoid drawing energy from the power grid, where a large part of it usually comes from fossil fuels, the energy storages can be used. It is in them that large amounts of energy can be cumulated, which are excess production in relation to the momentary demand resulting from the load on the power grids. Energy from the energy storage facilities can be used to produce green and yellow hydrogen in times of lower renewable energy production. Effective energy management using the latest control techniques and algorithms is very important in this area [105].

Transport, which refers to using hydrogen passenger cars, buses, and trucks will require distributed sources of hydrogen generation [106]. This means that the refueling stations for low-emission hydrogen, its production in electrolysis processes, and the acquisition of energy from renewable energy sources will have to be located next to each other [107–109]. As a result, this will prevent transporting hydrogen on longer routes, which is quite troublesome. Vehicles powered by hydrogen fuel cells are zero-emission at the point of use [110]. Moreover, they have all the advantages of battery-powered electric cars. These vehicles are quiet and are characterized by good traction and good acceleration [28]. Hydrogen vehicles also have braking energy recovery functions [111]. Therefore, vehicles powered by hydrogen fuel cells are ideal for driving in urban traffic. They can be an important component of the climate and energy transformation of transport companies [56]. Due to the need to completely replace all vehicles burning fossil fuels with low- or zero-emission vehicles, the demand for hydrogen will be increasing year by year [45]. It is worth mentioning that road vehicles are not the only vehicles that require ecological drive systems and alternative fuels. Hydrogen fuel cells are already successfully applied to power floating ships [112,113], rail vehicles, and airplanes. Such widespread use of hydrogen as a transport fuel will further increase the demand for its production. A large number of road, sea, and flying vehicles require appropriately prepared infrastructure for storing and refueling vehicles with hydrogen [114–116]. Hydrogen is safely stored on board of the vehicles in liquid or compressed form: up to 350 bar (buses) or 700 bar (passenger cars) [117]. The hydrogen fuel is then powered by hydrogen fuel cells, which generate electricity and heat while on board the vehicles. The types of fuel cells most commonly used in the automotive industry are PEM [118,119], SOFC [120], and MCFC [121].

The main goals presented in the article include the following:

1. A detailed analysis of the literature leading to the conclusion that hydrogen produced by electrolytic methods using renewable energy sources is the most promising medium for collecting energy and its use in various industries, especially in transport.
2. In the article, the authors proposed using a family of probability distributions to determine the amount of daily electricity produced by a photovoltaic system and thus to establish the possibility of producing yellow hydrogen from it.
3. This strategic model may be very useful for renewable energy developers who build photovoltaic systems intended specifically for the production of yellow and green hydrogen. Based on the model, they can estimate the size of the photovoltaic system needed to produce the assumed hydrogen volume.
4. The strategic model can also be used by producers of green and yellow hydrogen. Due to precise calculations, up to the probability distribution, the model allows us to calculate the probability of providing the required energy from a specific part of the energy mix.
5. The proposed model is universal and is suitable both for small amounts of yellow hydrogen produced and for its mass production by large ground-based photovoltaic systems.
6. The proposed model takes into account the geographical context of the photovoltaic system, as well as the engineering context regarding the components used and the method of their assembly. All these affect the amount of energy produced daily and the possibility of producing yellow hydrogen from it.

2. Research Methodology

Photovoltaic systems produced in the third decade of the 21st century are already Internet of Things devices. Photovoltaic inverters usually convert direct current produced by photovoltaic panels into alternating current present in the power grid. At short intervals, the inverters measure the generated voltage and current and send these values via wired or wireless transmission to the data cloud. On their basis, calculations can be made for the instantaneous power and the amount of energy produced. Measurement data are usually available to administrators of platforms monitoring the performance of photovoltaic systems and may be subject to processing. Currently, scientists are increasingly employing artificial intelligence algorithms to process measurement data from photovoltaic systems. The authors have extensive experience in classical statistical calculations related to energy production by photovoltaic systems. They also used recurrent neural networks to predict the amount of electricity produced from renewable energy sources for use in charging electric vehicles [122]. The metalog family of probability distributions turned out to be very effective, and the authors used it to select the power of the photovoltaic system for their electric vehicle and vice versa [123]. There are very strong similarities in the case of charging electric vehicles and producing yellow hydrogen from the energy obtained from the sun. In the first and second cases, users want the largest possible share of renewable energy in the mix intended for charging electric vehicle batteries or for powering hydrogen electrolyzers. Metalog is a flexible probability distribution that can be used to model a wide range of density functions using only a small number of parameters obtained from experts. Scientists prefer using the metalog family of distributions to describe processes in various fields of science such as theology [124], mathematics [125], and electronics [101].

The strategic model has yet another advantage. On its basis, it is possible to initially calculate the carbon footprint associated with the production of hydrogen from a mix of solar energy and the energy from the power grid. Unfortunately, in Poland, most of it derives from fossil fuels. However, the share of green energy in the Polish energy network is increasing year by year as a result of the investments in photovoltaic systems and wind turbines. Many European countries, such as Spain or Portugal, have very good climatic conditions for the production of large amounts of energy by photovoltaic systems [126].

The research, therefore, will concentrate on obtaining data from photovoltaic systems regarding the amount of energy produced at a specific time and processing it off-line using artificial intelligence algorithms. Based on the amount of energy produced by the photovoltaic system, calculations are made related to the possibility of producing yellow hydrogen from it. The research data flow diagram is presented in Figure 1.

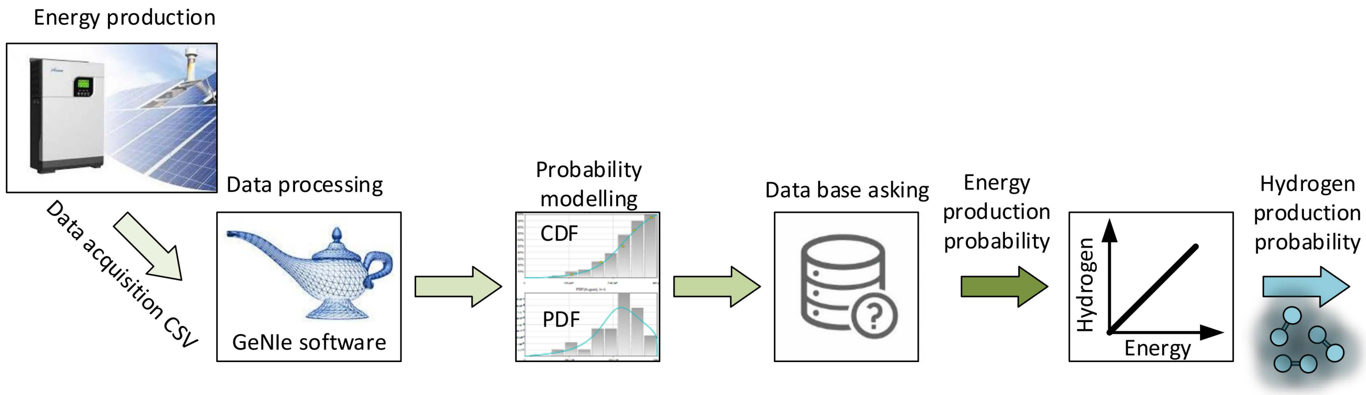


Figure 1. Data flow diagram.

Scientists use many mathematical methods to describe the amount of energy produced by photovoltaic systems and the amount of hydrogen produced. In many scientific works, archival performances of photovoltaic systems are subjected to traditional statistical analysis [127]. The authors have successfully used recurrent neural networks in the past to describe the amount of energy generated by a photovoltaic carport. However, the presented approach of using a family of probability distributions has a fundamental advantage over these methods. It allows us to query the knowledge base about the probability of generating a specific energy level and quickly assign it the amount of energy produced.

The authors first used a family of probability distributions to perform a strategic model for yellow hydrogen production. They used all the possibilities offered by this advanced analysis method to describe the amount of energy and hydrogen produced per day.

The advantages of the presented research method are as follows:

- The metalog family of distributions allows us to make calculations for a specific yellow hydrogen generation system placed in a specific location (the city of Lublin in Poland) and in a specific context (roof location, azimuth, shading).
- The metalog family of distributions allows us to determine percentiles in the production of electricity by a photovoltaic system and determine what its value will be with accuracy in terms of the probability distribution.
- The metalog approach talks about the composition of probability distributions. It is a complex distribution.
- From the shape of the probability density function (PDF), it can be concluded that there are several different contexts of operation of both the photovoltaic system and the entire yellow hydrogen generation system.
- Using the metalog family of distributions, we obtain information from a knowledge base, not a database. The difference is that in the database, the answer to the questions asked is obtained by searching the database. However, the knowledge base answers the question by running an inference algorithm.
- Using the strategic model, the user receives an answer about the amount of yellow hydrogen produced from a specific photovoltaic system with an accuracy of the probability distribution. This makes it possible to forecast the prices of produced hydrogen based on the share of photovoltaic energy in the total energy needed to produce the planned amount of hydrogen. This can be very helpful in green hydrogen price calculations for European Hydrogen Banks.

3. Research Results

3.1. Analysis of the Monthly Amount of Energy Produced by Photovoltaic Systems

The research used a photovoltaic system installed on the roof of WSEI University in Lublin (Figure 2). The system consists of 108 monocrystalline photovoltaic panels with a power of 460 Wp each. This gives a total power of 49.68 kWp. Therefore, its peak power is slightly lower than the maximum peak installation power currently in force in Poland, which is 50 kWp for a single individual user. The appearance of the photovoltaic system panels in the online monitoring platform is shown in Figure 1. The panels are tilted at an angle of 15°. Half of them were installed with an azimuth of 205°, and the other half with an azimuth of 116°. The installed photovoltaic system is the Internet of Things device. This is due to the presence of a photovoltaic inverter in the system, which continuously measures the current of the entire system and sends the collected information to the cloud. The information includes the measurement of the voltage and current generated by the photovoltaic system, which are used to calculate the instantaneous power and the electricity produced per day. From the very beginning, the photovoltaic system built on the roof of the university was also designed as a research laboratory for students and scientists in the fields of computer science, transport, logistics, and mechatronics. A power optimizer is installed on every second panel. Its task is to make accurate measurements of the power generated and energy produced on these two photovoltaic panels. This is very convenient when determining the amount of energy produced by panels with different installation azimuths. Yet the most important feature of such optimizers is the ease of identifying damaged photovoltaic modules. If one of the panels is damaged, the optimizer only turns off the damaged panel along with another panel connecting it to the optimizer. Additionally, an alert will be displayed on the online monitoring platform providing information on where exactly the damage is located. The photovoltaic system, which is the Internet of Things device, also generates a lot of data about the proper operation of the entire system. They can be processed online and off-line to obtain information. These, in turn, may be used in decision-making (business intelligence) in the area of energy management. For students of various fields, for example, they constitute the real measurement data for processing during laboratory classes.

Figure 2. Appearance of the arrangement of photovoltaic system panels with a peak power of 50 kWp in the online monitoring platform.

Figure 3 shows the amount of energy produced monthly by the tested photovoltaic system since its launch in March 2023. After a year of continuous operation, a general summary of the expected and actually produced electricity by the system can be made. From the beginning of operation to the present (12 April 2024), the photovoltaic system with a peak power of almost 50 kWp has produced 55.72 MWh of electricity. Figure 3 clearly shows the seasonality of energy produced by photovoltaic systems in Polish geographical and climatic conditions. The tested photovoltaic system capacity factor is 11.2%.

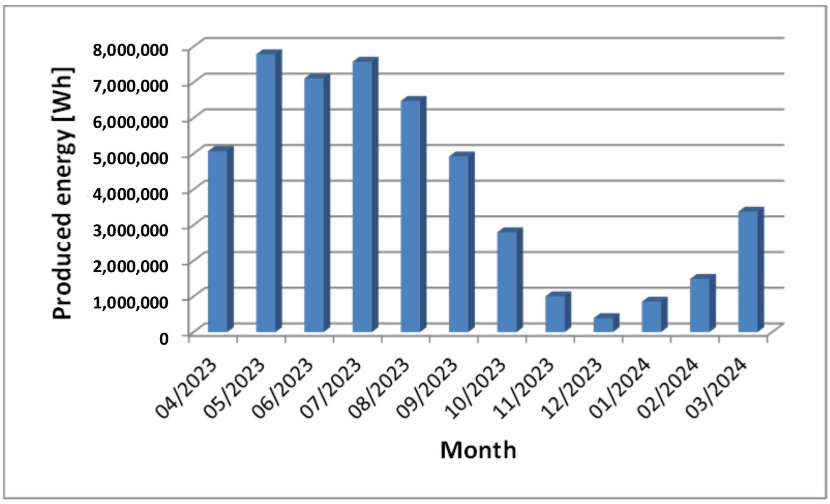


Figure 3. Amounts of energy produced by the photovoltaic system in individual months of 2023 and 2024.

In the autumn and winter months (November to February), energy production in Polish geographical and climatic conditions is very low. In order for investors in yellow hydrogen production systems to be able to make specific decisions related to the peak power of the photovoltaic installation being built, they must have specific quantitative data. The use of the metalog family of distributions to determine, with accuracy regarding the probability distribution, the amount of energy produced monthly and daily can provide valuable information. Based on the outcomes, the investor is able to estimate the amount of energy from renewable energy sources needed to produce yellow hydrogen. In this way, one can initially calculate the price of yellow hydrogen, taking into account the costs of energy from the photovoltaic system and the costs of energy from the power grid.

3.2. Analysis of the Daily Amount of Energy Produced by Photovoltaic Systems

The data on the monthly amount of energy generated by a 50 kWp photovoltaic system were downloaded from an online platform monitoring the performance of the photovoltaic system. One of the authors is the supervisor/manager of the tested photovoltaic system. The digitally exported data are stored in the form of a CSV file and then processed using the specialized GeNIe 4.0 Academic software [128].

The analysis is introduced with the amount of energy produced in April 2023. The research began with performing basic statistical calculations in the GeNIe program. The results of these studies are presented in Tables 1 and 2. During the thirty days in April 2023, the system produced the lowest daily amount of energy of just over 20,000 Wh, while the maximum value was almost 300,000 Wh. The conclusion is that on cold spring days in Polish climatic conditions, despite the short days, it is possible to produce significant amounts of energy. Low air temperature favors large amounts of energy production. The average area air temperature in Poland in April 2023 was 7.7 °C which was 0.9 °C lower than the norm. According to the quantile classification of thermal conditions, this month was rated as cold.

Table 1. Basic statistical analysis of the amount of energy produced in April 2023.

Count	30
Minimum	20,786
Maximum	297,384
Mean	169,091
StdDev	82,610.1

Table 2. Extended statistical analysis of the amount of energy produced in April 2023.

Probability	**April**
0.05	31,127
0.25	114,943
0.5	155,782
0.75	230,349
0.95	294,916
0.1333	50,000
0.2	100,000
0.3667	150,000
0.5667	200,000
0.8	250,000

The GeNIe 4.0 Academic software enables us to determine the empirical distributor and probability density function for various k coefficients (Figure 4). The probability density function chart demonstrates that high probability densities of energy produced in the month of April 2023 occur for both small and large daily amounts of energy generated.

Bimodality in the course of the probability density function (PDF) indicates a large diversity of energy produced per day [105]. The first extreme occurs for a daily energy production of approximately 100,000 Wh, while the second one occurs for a daily energy production of approximately 300,000 Wh. This means that a significant spread in the amount of energy is produced. The bimodal waveform of the probability density function (PDF) confirms a large standard deviation of 82,610.1 Wh. Therefore, probability analysis using the metalog family of distributions is an extension of basic statistical calculations [129].

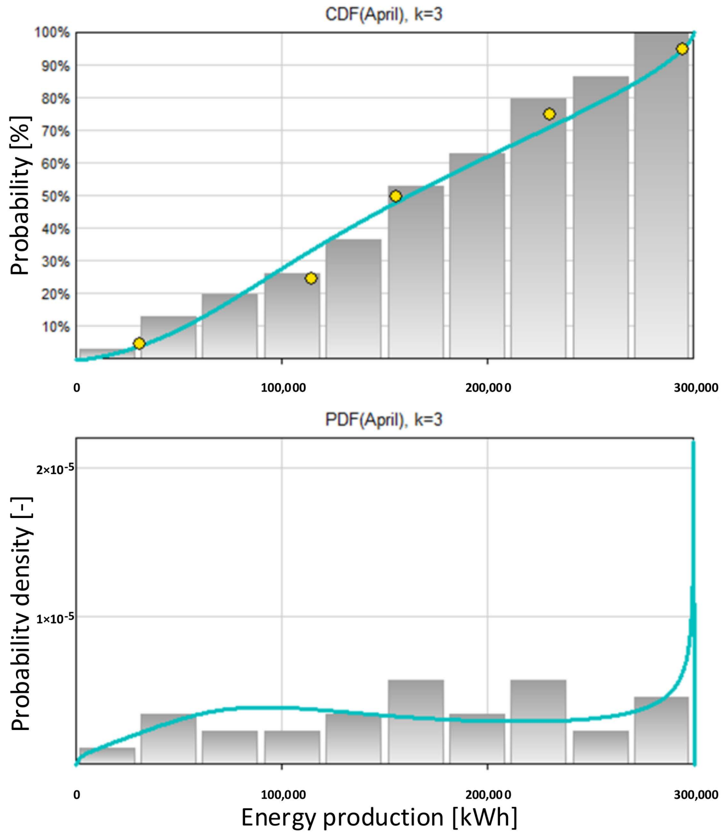


Figure 4. Cumulative distribution function (CDF) (sea color line) and quantile parameters (yellow symbols) and probability density function (PDF) (sea color line) for the k = 3 factor for energy produced by a 50 kWp photovoltaic installation in April 2023.

As is clearly visible from the raw data presented in Figure 3, the largest amount of energy produced took place in May 2023. The spring month of May in Polish climatic conditions in 2023 was characterized by a large number of sunny days as well as quite low temperatures and high windiness, which positively affected the amount of energy produced by photovoltaic energy systems. In terms of precipitation, May 2023 was dry and very dry in most of Poland and extremely dry in the north. The average amount of precipitation for Poland was 36.0 mm, which was 54.9% of the norm for the period 1991–2020 [130]. The photovoltaic system produced 7,786,250 Wh of energy (almost 8 MWh) that month.

Basic and extended statistical calculations were also performed for the data from the photovoltaic system. These are presented in Table 3. The minimum value of energy produced per day in May 2023 was 36,784 Wh, the maximum value was 339,226 Wh, and the average value of energy produced was 251,169 Wh, with a standard deviation of 99,263 Wh. The metalog family of distributions allows for more advanced statistical analysis, including the determination of quantiles, as shown in Table 4.

Table 3. Basic statistical analysis of the amount of energy produced in May 2023.

Count	31
Minimum	36,784
Maximum	339,226
Mean	251,169
StdDev	99,263

Table 4. Extended statistical analysis of the amount of energy produced in May 2023.

Probability	**May**
0.05	51,124
0.25	241,694
0.5	288,847
0.75	323,446
0.95	333,686
0.0323	50,000
0.1613	100,000
0.1935	150,000
0.2258	200,000
0.3226	250,000
0.5161	300,000

The cumulative distribution function (CDF) for the coefficient k = 3 for energy produced by a photovoltaic installation with a capacity of 50 kWp in May 2023 is presented in Figure 5. The polynomial with the coefficient k = 3 reflects the course of the cumulative distribution function (CDF) very well. The probability density function plot (PDF) shows that high probability densities only occur for large daily amounts of energy generated in May 2023. This function has only one extreme, occurring for large amounts of energy produced (see Figure 6).

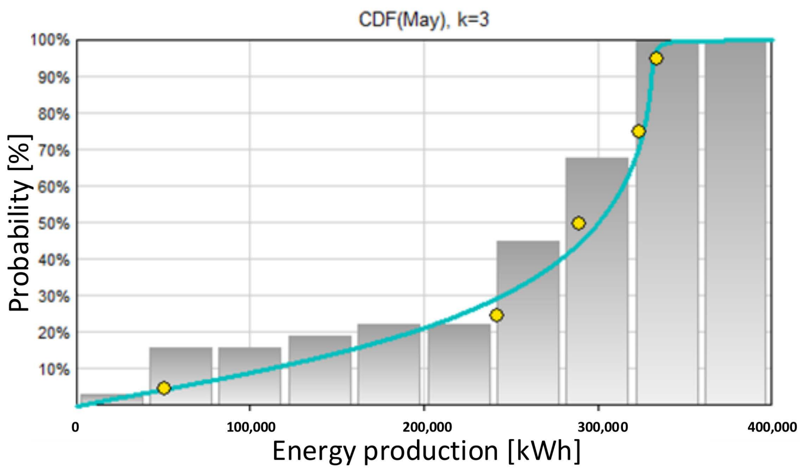


Figure 5. Cumulative distribution function (CDF) (sea color line) and quantile parameters (yellow symbols) for the k = 3 factor for energy produced by a 50 kWp photovoltaic installation in May 2023.

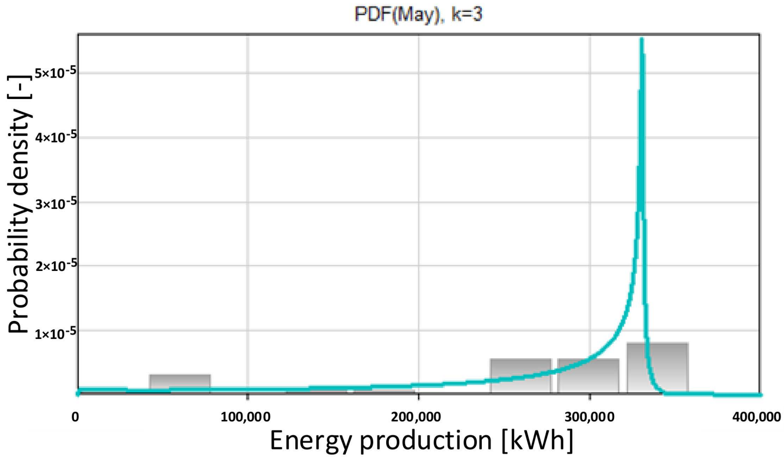


Figure 6. Probability density function (PDF) (sea color line) for the k = 3 factor for energy produced by a 50 kWp photovoltaic installation in May 2023.

In the following months (June, July, August, and September), large amounts of energy produced by the photovoltaic system should also be expected. This is confirmed by the data from the tested 50 kWp photovoltaic installation, which are presented in Figure 2. The cumulative distribution function (CDF) and the probability density function (PDF) for the energy produced by the 50 kWp photovoltaic installation in August and September 2023 appear in Figure 7.

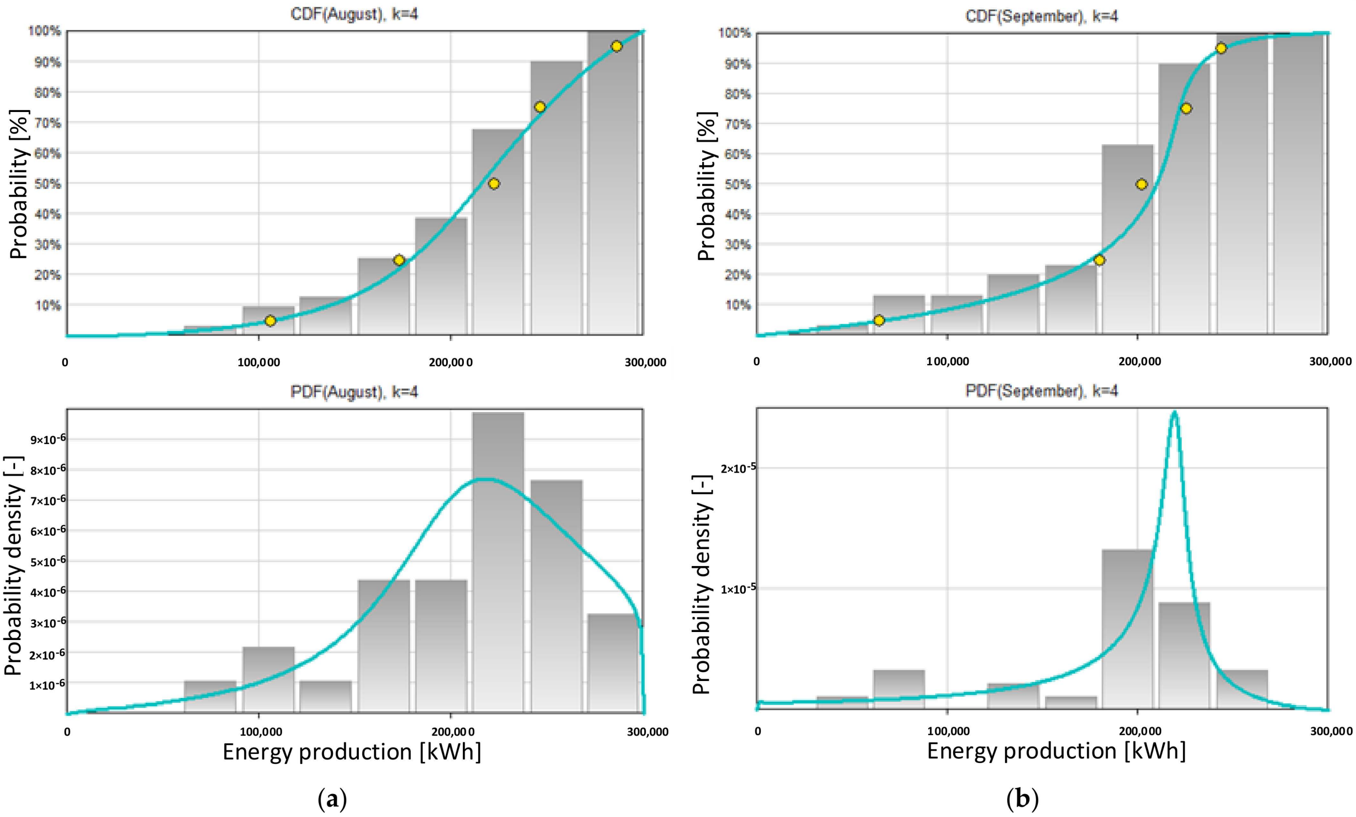


Figure 7. Cumulative distribution function (CDF) (sea color line) and quantile parameters (yellow symbols) and probability density function (PDF) (sea color line) for energy produced by a 50 kWp photovoltaic installation in August (**a**) and September (**b**) 2023.

The next step in the analysis was to obtain the information from the knowledge base. Using the metalog family of distributions, we obtain the information from the knowledge base and not from a database. The difference is that in the database, the answer to the questions asked are obtained by searching the database, while the knowledge base answers the question by running an inference algorithm [131]. This approach is like asking the question: What if? Determining the probability for a given daily amount of energy produced requires a simulation process that uses the determination of the inverse function of the empirical distributor. The GeNIe 4.0 Academic software has built-in families of metalog distributions and allows for quick determination of the empirical distributor, probability density function, and a simple way of obtaining information from the knowledge base. Then, the probability of daily energy production of 50,000, 100,000, 150,000, 200,000, 250,000, and 300,000 Wh was determined. The calculation results are included in the lower rows of Table 5.

Table 5. Extended statistical analysis of the amount of energy produced in August 2023.

Probability	August
0.05	106,326
0.25	173,298
0.5	222,387
0.75	246,430
0.95	286,412
0.0323	100,000
0.1290	150,000
0.3871	200,000
0.8065	250,000

The probability of producing an amount of electricity less than or equal to 50,000 Wh is 1. This means that on every day of this month, the daily energy production was greater than 50,000 Wh. The probability of generating an amount of electricity less than or equal to 100,000 Wh during one August day in 2023 is 0.0323. This means that producing more than 100,000 Wh of energy is 0.9677. Similar calculations were performed for other levels of the amount of energy produced. The results of the probability of daily energy production produced by a 50 kWp photovoltaic installation in August 2023 are presented in Table 6. Identical calculations were carried out for the daily energy produced in all tested months. The results of these calculations can be found, among others, in the lower rows of the Tables 2 and 4.

Table 6. Results of the probability of daily energy production produced by a 50 kWp photovoltaic installation in August 2023.

Energy [Wh]	Probability $\leq$	Probability >
50,000	0	1
100,000	0.0323	0.9677
150,000	0.1290	0.871
200,000	0.3871	0.6129
250,000	0.8065	0.1935
300,000	1	0

The next analyzed example is the amount of energy produced daily by the same 50 kWp photovoltaic system in January 2024. The amounts of energy produced per day are as follows: minimum—1170 Wh; maximum—98,076 Wh; and average—27,521.8 Wh. The standard deviation is 22.835 Wh (see Table 7).

Table 7. Basic statistical analysis of the amount of energy produced in January 2024.

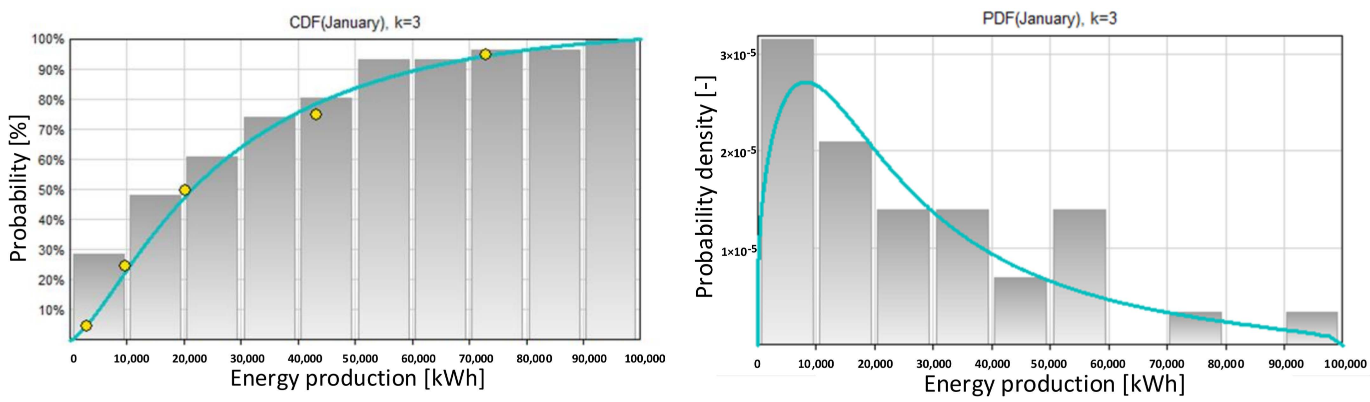
Count	31
Minimum	1170
Maximum	98,076
Mean	27,521.8
StdDev	22,835

The probability of daily energy production produced by a 50 kWp photovoltaic installation in the winter month of January 2024 is only able to reach the first level of energy generated per day of 50,000 Wh (see Table 8). Moreover, the probability of obtaining it is very small because it is $1 - 0.8065 = 0.1935$. These analyses lead to the conclusion that in Polish geographical and climatic conditions during the winter months, the production of electricity by photovoltaic systems is very small compared to the production of energy in the summer months. The month with the lowest monthly energy production in Poland is usually December. In February, the monthly amount of energy produced from a photovoltaic system with a peak power of 50 kWp usually exceeds 1,000,000 Wh. In March 2024, the monthly production exceeded 3,000,000 Wh, with an average daily production of 108,968 Wh.

Table 8. Extended statistical analysis of the amount of energy produced in January 2024.

Probability	January
0.05	3097
0.25	9751
0.5	20,384
0.75	43,234
0.95	72,972
0.8064	50,000

The cumulative distribution function (CDF) and the probability density function (PDF) for the energy produced by a 50 kWp photovoltaic installation in January 2024 are presented in Figure 8.



(**a**) (**b**)

Figure 8. Cumulative distribution function (CDF) (sea color line) and quantile parameters (yellow symbols) (**a**) and probability density function (PDF) (sea color line) (**b**) for energy produced by a 50 kWp photovoltaic installation in January 2024.

Small daily amounts of energy produced in the winter months mean a small share of energy from renewable energy sources in the total energy needed to power electrolyzers producing yellow hydrogen. This will mean much higher costs of hydrogen production and it will be less low emission. The solution to this problem is the production of the energy mix from photovoltaic systems and other renewable energy sources in the form of wind energy [132].

3.3. Calculations of the Amount of Hydrogen Produced

Currently, there are many types of water electrolyzers available on the market for hydrogen production. The oldest and most mature technology is characterized by alkaline electrolyzers. Recently, electrolyzers with proton exchange membrane (PEM) have become very popular. Solid oxide electrolyzers (SOE) are designed to operate at high temperatures. They can be powered by waste steam rather than liquid water which affects their performance. The newest type of water electrolyzers are electrolyzers with anion exchange membrane (AEM). At the same time, this type is the least tested in the area of long-term operation. PEM and AEM electrolyzers, due to their efficiency and potential dynamics, are promising methods of producing hydrogen from wind energy and photovoltaics, which, by their nature, are variable suppliers of electricity. As a result, much research and development are being carried out to improve the performance and reduce the costs of these technologies. Proton exchange membrane electrolyzers (PEM) use a semipermeable membrane made from a solid polymer and designed to conduct protons. While PEM electrolyzers provide flexibility, fast response time, and high current density, the widespread commercialisation remains a challenge primarily due to the cost of the materials required to achieve long lifetimes and performance. Specifically, the highly acidic and corrosive operating environment of the PEM electrolyzer cells calls for expensive noble metal catalyst materials (iridium, platinum) and large amounts of costly titanium. This poses a challenge to the scalability of PEM electrolyzers. The anion exchange membrane electrolyzers use a semipermeable membrane designed to conduct anions. They are a viable alternative to PEM, with all the same strengths and several key advantages that lead to lower cost. Due to the less corrosive nature of the environment, steel can be used instead of titanium for the bipolar plates. Furthermore, AEM electrolyzers can tolerate a lower degree of water purity, which reduces the input water system's complexity and allows for filtered rain and tap water.

According to the document "Polish hydrogen strategy until 2030", 9 L of water and approximately 50 kWh of electricity are required to produce 1 kg of hydrogen [133]. This corresponds to a system efficiency of 66.6% [134]. This amount may change if a more efficient process is used [135–138]. With the Enapter AEM electrolyzer, we need 4.8 kWh to produce 1 Nm^3 of hydrogen [139]. That means it takes 53.3 kWh to produce 1 kg of hydrogen (compressed at 35 barg and with a purity of ~99.9%). A total of 1 kg of hydrogen contains 33.33 kWh/kg (lower heating value), so this electrolyzer already has an efficiency of 62.5%. It is important to compare the same parameters in different types of electrolyzers, namely, power input, hydrogen production, pressure, and purity. These are very different for different manufacturers. System efficiencies (not stack efficiencies) need to be compared. These data are presented for a 2.5 kW electrolyzer that is scalable to 1 MW. Various electrolyzer manufacturers present the efficiency of their products under various operating conditions. For instance, for a large electrolyzer with a power of 6 MW, the manufacturer declared a stack efficiency higher heat value (HHV) of 75.9% [71]. This applies to the HyProvide® X-1200 Prototype model with a hydrogen efficiency of 1200 Nm^3/h (107 kg/h) with a purity of 99.998% and a pressure of 35 barg. The declared energy consumption is 54.7 kWh/kg. The efficiency of the entire hydrogen generation system calculated on this basis is 60.1%. Scientists are more accurate than sellers when providing data on the efficiency of electrolyzers. PEM electrolyzer data were also found in the literature [119]. At the rated power condition, defined as 2 A/cm^2 at 1.9 V, 80 °C, and 30 bar H_2 pressure, the stack/system efficiency is 65.3%/60.3% at beginning of life (BOL), decreasing to

59.3%/53.9% at end of life (EOL). The peak stack/system efficiency is 76.3%/70.2% at BOL, decreasing to 71.2%/65.6% at EOL.

The dependence of the monthly hydrogen production on the amount of electricity supplied to the electrolyzers is shown in Figure 9. A similar characteristic of the relationship between the amount of hydrogen produced and the electricity consumed can be found in the literature [140]. An amount of 300 kWh of electricity is required to produce 6 kg of hydrogen. This amount of hydrogen is enough to fully refuel the Toyota Mirai hydrogen vehicle, which translates into a total range of this vehicle of over 600 km.

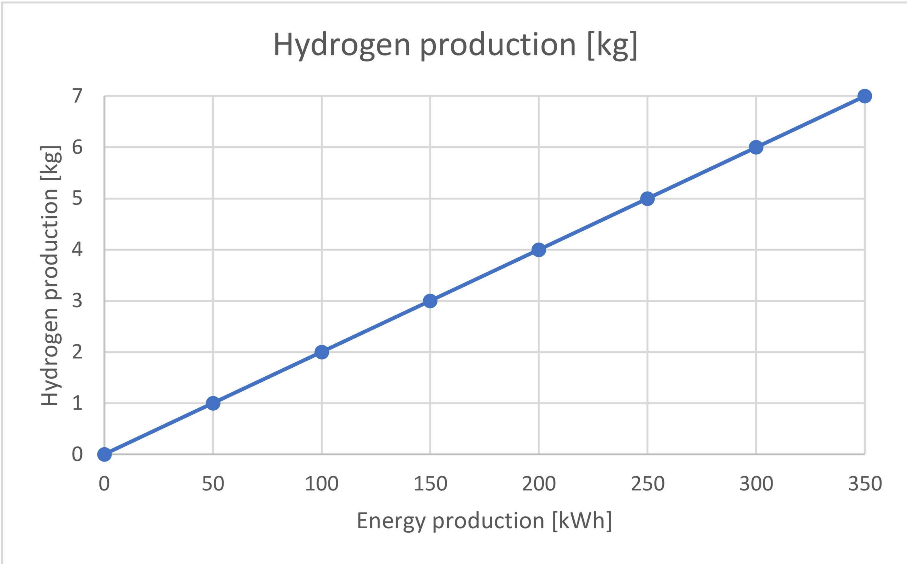


Figure 9. Dependence of daily hydrogen production on the amount of energy supplied.

The algorithm for selecting a photovoltaic installation for the required amount of yellow hydrogen produced, presented by the authors, is a strategic model on which the hydrogen management of a given company can be based on. The advantage of the presented strategic model is its scalability, presented in the form of several levels of energy produced by photovoltaic systems, which translate into the amount of hydrogen generated monthly.

4. Discussion

In Polish geographical and climatic conditions, a photovoltaic system with a peak power of 50 kWp is able to generate over 50 MWh of energy per year. However, monthly energy production is very dependent on seasonality. Nonetheless, for the production of yellow hydrogen, calculations of daily electricity production are most useful. Figure 10 shows the probability that a photovoltaic system with a peak power of 50 kWp will produce certain levels of daily electricity production. In Polish climatic conditions, it is able to generate more than 50 kWh of electricity per day with probability 1 in the months from May to November. By reviewing the relationship presented in Figure 9, it can be estimated that this is the amount of energy needed to produce 1 kg of hydrogen. The system produced 100 kWh per day with probability equal to 1 only in July 2023. This is the amount of energy corresponding to 2 kg of hydrogen. One can count on the production of 100 kWh of energy per day with a probability equal to or greater than 0.8 in the months from April to October. The production of energy greater than 200 kWh of energy per day with a probability greater than or equal to 0.5 can be counted on in the months from May to September. The system achieved maximum daily production exceeding 300 kWh only in the months from May to July, and with a probability much lower than 0.5.

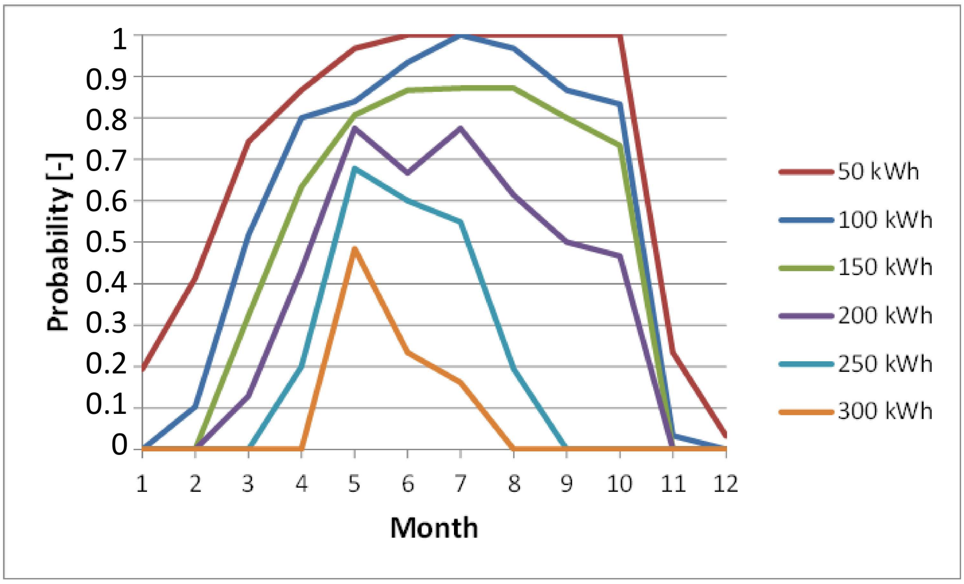


Figure 10. The probability of producing daily amounts of energy via the photovoltaic system in each month of the year.

Taking into account the relationship presented in Figure 8, it is easy to convert the probability of producing daily amounts of energy by the photovoltaic system in individual months of the year into the probability of producing daily amounts of yellow hydrogen (see Figure 11). Indeed, this assumption takes into account the fact that all the energy produced is used to produce yellow hydrogen. Due to technical limitations related to the required load stability of hydrogen electrolyzers, the missing amount of energy must be taken from the power grid.

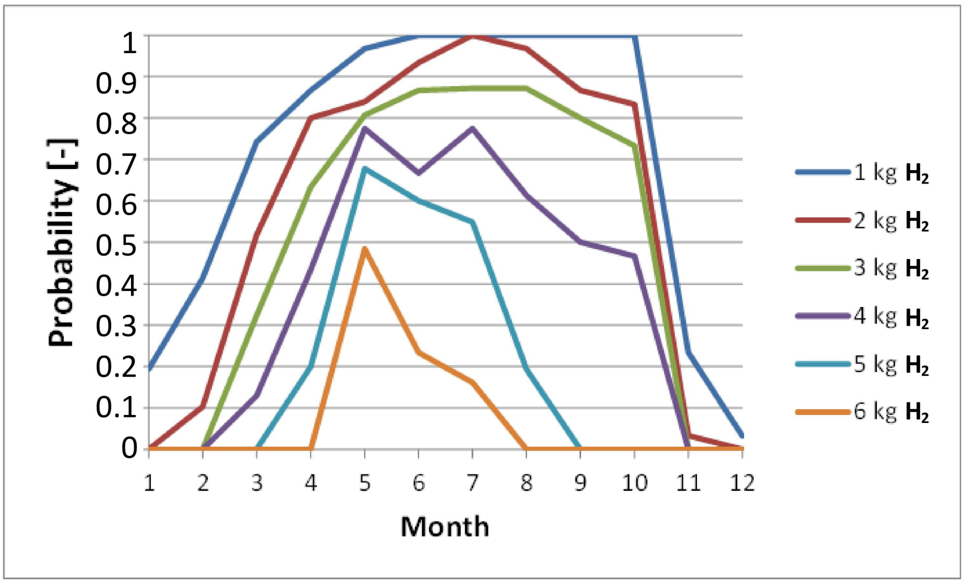


Figure 11. Probability of producing daily amounts of yellow hydrogen.

The algorithm for selecting a photovoltaic installation for the required amount of yellow hydrogen produced, presented by the authors, is a strategic model on which the hydrogen management of a given company can be based. The major advantage of the presented strategic model is its scalability, presented in the form of several levels of energy produced by photovoltaic systems, which translate into the amount of hydrogen generated monthly. It is worth emphasizing once again that the presented calculations are made for a specific photovoltaic system in a given location and in a specific context (including time). Therefore, when planning to build a new renewable source of electricity intended specifically for the production of yellow hydrogen, it is worth finding a similar system located in the immediate vicinity. Many manufacturers of photovoltaic inverters run open online platforms from which one can obtain information on the daily, monthly, and annual electricity production of a photovoltaic system with a specific peak power. Having the data on the amount of energy produced, anyone can use the strategic model of hydrogen production from energy derived from a dedicated photovoltaic system presented in this article.

The obtained research shows that the production of yellow hydrogen in Polish geographical and climatic conditions is possible only in some months of the year. This means that the hydrogen produced can also be used seasonally. For example, it may be used for the seasonal transport of tourists in the summer using hydrogen vehicles. The demand for hydrogen results from the number of vehicles refuelled with this fuel and their driving conditions [141].

The amount of energy produced by photovoltaic systems in one day may vary significantly, which may affect the load on electrolyzers. The use of stationary energy storage units (power banks) may be a way to increase the amount of yellow hydrogen produced when the sun is not shining. The authors intend to continue research in this direction. The next work will include the amount of excess energy production above the assumed own needs (self-consumption), storing it in energy warehouses and using it to produce yellow hydrogen. This will be profitable thanks to the decreasing prices of lithium-ion batteries themselves and the second life of traction batteries from electric vehicles [142,143].

The production of yellow hydrogen will be much more profitable in countries with greater sunlight. In European competitions supporting the production of low-emission hydrogen, owners of photovoltaic systems in Spain may offer much lower prices for the produced hydrogen than those in Poland. The plant factor for photovoltaic systems located in southern Europe is much higher than for Polish systems. The authors plan to publish comparative data on the possibility of producing yellow hydrogen in Poland, Hungary, and Spain in the near future. These data can show significant differences in the amount of hydrogen produced from the same peak power of a photovoltaic system located in different countries. But will these differences be large enough to cover the costs associated with transporting the produced hydrogen to the receiving site? Or maybe it is better to produce and use it locally in the so-called dispersed systems? There are still many questions that scientists need to answer in order to effectively implement the climate and energy transformation. Published case studies of the transformation, both positive and negative, may be of great importance.

5. Conclusions

The analyses presented in the article suggest that the daily production of electricity in Polish geographical conditions is characterized by high variability due to the seasons. This, in turn, directly affects the possibility of producing yellow hydrogen.

The strategic model presented in the article allows users to calculate, with accuracy to the probability distribution, the amount of daily energy produced by photovoltaic systems with a specific peak power. Using the model in question, it is possible to calculate the expected amount of electricity produced daily from the photovoltaic system and the corresponding amount of yellow hydrogen produced. Such a strategic model may be very useful for renewable energy developers who build photovoltaic systems intended specifically for the production of yellow and green hydrogen. Based on the model, they can estimate the size of the photovoltaic farm needed to produce the assumed hydrogen volume. The strategic model can also be used by producers of green and yellow hydrogen. Due to precise calculations, up to the probability distribution, the model allows us to calculate the probability of providing the required energy from a specific part of the energy mix.

The proposed method may also have a positive impact on the power grid. Due to these calculations, it is possible to increase the auto-consumption rate of energy produced by the photovoltaic system. All energy produced will be utilized to produce hydrogen instead of being fed into the power grid at an unfavorable price. The strategic model for yellow hydrogen production can have a very wide range of applications. It can be used by engineers and economists designing photovoltaic systems and hydrogen production systems. It can be implemented to plan the climate and energy transition of companies producing large amounts of hydrogen for industrial and transport purposes. It can also be part of advanced software for modeling energy production and hydrogen production systems.

The periodicity (due to day/night) and seasonality (due to summer/winter) of electricity production using photovoltaic systems mean that the production of larger amounts of hydrogen cannot be based solely on this Renewable Energy Source. The authors intend to continue the research undertaken. The next step will be to analyze the possibilities of producing green hydrogen using energy from an energy mix consisting of photovoltaic systems and wind turbines. The combination of energy streams produced by various renewable energy sources will enable the production of green hydrogen throughout the day.

However, the proposed method has some limitations. To fully benefit from it, one must be able to interpret the course of the probability density function (PDF). Such competences are held by the scientists, not the technical staff in energy producing plants. To facilitate the interpretation of the obtained results, in the future work, the authors intend to develop a system for the automatic interpretation of the obtained results, along with specific recommendations related to their use in energy management.

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Abbreviations

RES	Renewable Energy Source
PEM	Proton Exchange Membrane
AEM	Aion Exchange Membrane
AFC	Alkaline Fuel Cell
SOFC	Solid Oxide Fuel Cell
SOE	Solid Oxide Electrolyzer
MCFC	Molten Carbonate Fuel Cell
FCV	Fuel Cell Vehicle
PV	Photovoltaics

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