The Archives of Automotive Engineering – Archiwum Motoryzacji Vol. 100, No. 2, 2023
https://doi.org/10.14669/AM/166655

SELECTION OF THE PHOTOVOLTAIC SYSTEM POWER FOR THE ELECTRIC VEHICLE

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Abstract

The article presents a method of a photovoltaic system power selecting for proper electric vehicle. At the beginning, the characteristics of the electric vehicle itself and its traction batteries were made in order to determine the method of its charging. In the presented studies, measurement data from the operation of real photovoltaic systems was recorded and processed. The algorithm used includes examining the energy consumption profile of the owner's residential building. The combined demand for electricity of the electric vehicle and the building made it possible to determine the planned photovoltaic system. The authors presented three possibilities of its location. It can be installed on the roof of the building, on the ground next to the building or on the carport under which an electric vehicle can be parked. Finally, the Metalog family of probability distributions was used to analytically validate the power choice of the photovoltaic system. The authors have developed an algorithm using human and artificial intelligence that helps to properly select the power of the photovoltaic system for the vehicle.

Keywords: electric vehicle; photovoltaic system; energy generation; battery charging; metalog

1. Introduction

In the third decade of the 21st century, several trends are clearly visible in Europe. The first of them concerns the generation of electricity from Renewable Energy Sources (RES) [35]. The second concerns the replacement of the traditional drive of vehicles using internal combustion engines for vehicles powered by electric motors [9, 37] and hybrid drives [10, 32]. The third trend concerns the production of hydrogen [31] and its use to power vehicles with hydrogen fuel cells [12]. Hydrogen can also be produced using RES [27]. This approach contributes to the reduction of greenhouse gas emissions by means of transport [4, 5]. Environmental awareness encourages both individual customers and vehicle fleet owners [7, 16] to purchase low-emission or zero-emission vehicles.

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Generating electricity from RES is possible thanks to significant progress in science and technology. Among the most important renewable sources are water energy, wind energy and solar energy. In this article, we will only deal with the last of these sources. Generating electricity from solar radiation is possible thanks to the photovoltaic phenomenon that occurs in selected semiconductor materials. These materials are used to make very thin but large-surface photovoltaic panels. The individual panels are then connected in series to obtain higher voltages. Photovoltaic panels are mounted on the roofs of buildings, on the ground and on special structures called carports [26], under which vehicles can be parked [22]. Flexible photovoltaic panels can also be mounted on the roofs of vehicles. However, the small active area of photovoltaic panels causes the production of small amounts of energy that are not able to significantly increase the range of electric vehicles. The authors will not discuss this type of photovoltaic systems in the article. Small installations with a peak power of up to 50 kWp are called photovoltaic micro-installations. The larger ones are called photovoltaic farms or photovoltaic power plants.

In the field of photovoltaic systems, the continuous development of individual components is observed. Scientists are studying new materials that have even greater efficiency in converting solar radiation into electricity and will be cheaper to produce. Perovskites, in the development of which Polish scientists have a large share, are promising in this area [25]. Another area of research is to increase the durability of panels and diagnostics [13] of entire photovoltaic systems and their remote monitoring [24]. An important component of each photovoltaic installation is the energy converter in the form of an inverter. At present, these are very efficient electronically controlled systems. Due to their function of converting direct current generated by the panels into alternating current present in the power grid of buildings, inverters make accurate energy measurements. Thanks to such measurements, users of photovoltaic systems are informed about the current power of the system and the amount of energy produced. The inverters already have the Internet of Things functions as standard, thanks to which they send data packets about the system operation to the cloud server. This data can then be processed and used for energy management. One of the authors is the Supervisor/Management of several photovoltaic systems of different power. Thanks to its function, it has access to various market solutions and compares them with each other. This role results from working at the Lublin Science and Technology Park (LST-P), whose mission is to combine science and business. The LST-P has developed an advanced infrastructure for generating electricity from the Sun [14].

The second trend mentioned at the beginning of the article is electromobility. In Europe, this trend began to appear in 2012, when several previously popular models of electric vehicles entered the market. In the following years, a real revolution took place in this area. Electric vehicles are breaking sales records despite high prices. However, this means that users see and appreciate the advantages of electric vehicles. They are ecological because they do not emit hazardous components at the place of use [23]. They are even more ecological when energy from RES is used to charge their batteries [21, 30]. Electric vehicles are also quiet and have good driving performance. Heavy traction batteries built into the chassis of the vehicle lower the center of gravity of the whole vehicle and contribute to good road holding when cornering. Despite the usually higher weight of electric vehicles compared to their combustion counterparts, they have very good performance in the form of acceleration. This advantage results from the torque characteristics of the electric motor, which reaches a high value even at low rotational speeds. Scientists and engineers from automotive concerns are constantly working on increasing the range of electric vehicles [28].

There are different types of electric motors in currently produced electric vehicles. Among them, the most popular are synchronous motors (PMSM) and asynchronous AC motors (PMAM) with permanent magnets [41]. Of course, wound-rotor motors are still used in modern vehicles. In higher-class vehicles and sport utility vehicles (SUVs), manufacturers use two traction motors, one for each axle of the vehicle. Less popular is the use of brushless DC motors (BLDC) for driving vehicles and the installation of individual motors in the hubs of each wheel of the vehicle. The latter solution is more popular in the case of electric buses.

Electric vehicles require a large amount of electricity to cover long distances. It is collected in traction batteries and managed by the BMS (Battery Management System) [11]. At present, the energy capacity of battery packs reaches 100 kWh. With this amount of energy, vehicles can travel over 500 km. With the increase in the number of electric vehicles, the charging infrastructure needs to be developed [40]. Many charging points for electric vehicles are being built along motorways and within cities. They are characterized by different standards for supplying electricity to the traction batteries of electric vehicles. Typically, these are access posts for 230 V single-phase AC with a Schuko plug or 400 V three-phase AC with a Type 2 plug. The latter provide 11, 22 or 40 kW to the on-board charger in the electric vehicle. It is an AC/DC energy converter. Quite different devices are the so-called DC fast chargers. They are stationary access points for charging electric vehicle batteries with direct current DC with voltages up to 800 V. They have a power of 40 kW to 350 kW and allow charging electric vehicles batteries in a very short time [15, 39].

The main advantages of electric vehicles include the fact that they are quiet and have energy recovery functions during braking [38]. A major challenge is to determine the actual demand of an electric vehicle for electricity [29] and the life expectancy of lithium-ion batteries as a result of their fast charging [1, 8]. Currently produced electric vehicles represent a major development step towards autonomous vehicles. More and more vehicles with combustion and electric drive are equipped with electric components [6], which are more economical and easier to control [17]. There is a constant increase in technologies supporting the active and passive safety of the vehicle and facilitating the parking of the vehicle.

Users of electric vehicles very often look for ways to charge their vehicles' batteries as cheaply as possible [33, 34]. To do this, they charge them in their own garage at night using tariffs for lower energy prices. However, the way to become independent from the ever-increasing prices of electricity is to have own photovoltaic installation that produces energy to power electrical receivers at home and to charge electric vehicles.

https://doi.org/10.14669/AM/166655

The aim of the article is to research and develop an algorithm using human and artificial intelligence designed to support the selection of the photovoltaic system power for the electric vehicle. The purpose of the research results from the demand of owners of electric vehicles for this type of technical and scientific support.

2. Algorithm for selecting of the photovoltaic installation power for proper vehicle

2.1. Characteristics of an electric vehicle

The authors have chosen one of the best-selling electric vehicles in Europe by 2020 – Renault Zoe. The choice results from the very large number of such vehicles in Poland. Renault Zoe is a B-segment city car designed to transport 5 people. The tested model came from 2019 and had traction batteries with an energy capacity of 41 kWh. The manufacturer stated a range of 300 km on a single battery charge. The authors tested their car in various road and weather conditions with various loads (only the driver and 5 people on board). Achieving a range of 300 km is possible on a warm (but not hot) day in country driving at speeds up to 100 km/h with one or two people on board.

The traction battery is charged via the Type 2 charging socket located in the front part of the vehicle under the brand logo. The vehicle was equipped with an on-board charger with a maximum power of 22 kW. In this configuration, the vehicle can be powered by a charging pole with a power of 7, 11 and 22 kW. Of course, in the case of a charging pole with a power of less than 22 kW, the power with which the charger works is also lower. The vehicle has also been equipped with a charging cable with a Schuko plug. This charging option requires more than 20 hours of full battery charging. However, it does not require any additional investments from the owner of the electric car. Those who want to charge the traction batteries of their electric vehicle faster usually install wall-mounted chargers on the wall of the building facade or in the garage (so-called wallbox). They already have a three-phase power supply and usually have a power of 7 kW or 11 kW. Wallboxes and charging points with a power of 22 kW are also an option, but in domestic conditions it involves the expense of increasing the ordered power and is rare. The tested vehicle while being charged from a 22 kW pole is shown in Figure 1.

Fig. 1. Tested vehicle while charging from a 22 kW pole

The most important characteristics of an electric vehicle, apart from the battery capacity and the average electricity consumption needed to drive 100 km, should also include the daily and monthly distance covered. According to the data presented in various sources, the average daily range in Europe is less than 30 km. However, each owner should make his own calculations. Useful information in this regard is also contained in the Central Register of Vehicles and Drivers (http://www.cepik.gov.pl/). Just log in to the portal and check the distances covered between annual inspections at Vehicle Inspection Stations. However, many people buy vehicles powered by alternative fuels (LPG, CNG) as well as electric vehicles to drive economically over longer distances. There are people who commute 50 km each day from home to work and back. Such people therefore cover about 2,000 km a month just for work. Adding weekend trips, the annual mileage of such a car can easily amount to 30,000 per year. How much electricity does it take to cover such a distance? If a vehicle is able to drive 300 km on a single charge, then 100 full charges are needed to cover 30,000 km, which gives 100 x 41 kWh = 4,100 kWh.

It should also be remembered that the electric vehicle is only one of the energy receivers that will use the energy produced by the photovoltaic system. It is therefore necessary to determine the energy needs of owned building.

2.2. Determining the energy needs of the building

The easiest way to determine the energy needs of a building is to analyze electricity bills. In settlements with the distributor and seller of electricity, we can easily find the amount of energy consumed in given periods of time and its cost. Annual summaries can also be found there. Even faster, information on our consumption can be found on the platform https://ebok.gkpge.pl/. In the Your consumption tab, can be found charts of total energy consumption in selected billing periods, as shown in Figure 2.

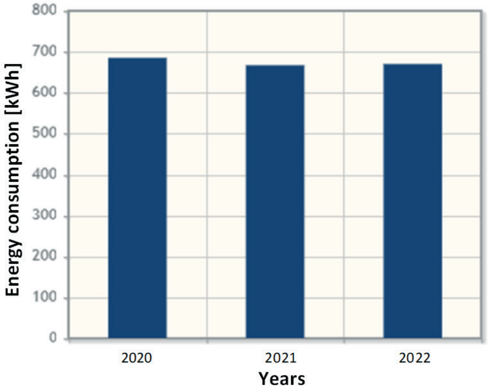


Fig. 2. Total consumption in semi-annual periods read from the PGE platform

However, the best way to know the energy needs of owned building is to prepare an energy consumption profile using the OneMeter system. It is an innovative system for monitoring, analysis of consumption and production as well as effective use of electricity. It includes:

- OneMeter device – a small, battery-powered device that reads measurement data from an energy consumption meter.
- OneMeter application – an application for Android smartphones, used for data synchronization from the device (via Bluetooth Low Energy) and as an online gateway.
- OneMeter Cloud – an internet platform with readings preview, profiles, charts, reports, data export and API access.

The main advantages of OneMeter are simplicity and universality [3]. The system is used by both home users as well as enterprises and companies optimizing energy costs in large manufacturing companies (ESCo). The Onemeter device works with meters in both single- and three-phase installations. It is mounted on the optical port of the meter and obtains measurement data via the IEC 62056-21 protocol. OneMeter in the Home version collects data on active energy consumption and allows to track costs, and in the Business version it also provides data on reactive energy and allows to adjust the ordered power. If OneMeter is installed on a bidirectional meter, the user also receives information about the energy fed into the grid, which is important for owners of photovoltaic (PV) installations.

Very interesting and useful are graphs of consumption profiles in the Power Consumption tab [2]. The graph in Figure 3 shows the active power consumption profile during the day. The minimum, maximum and average values are shown in 15-minute intervals. The profile clearly shows the night consumption values when the PV system is not in operation. During the day, the impact of the energy produced by the photovoltaic system is visible, which reduces the power consumed by the building to values close to zero during the hours of sunlight. The maximum values occur on days of very poor insolation, when the power generated by the photovoltaic system is not able to cover the building's demand. The maximum values therefore tell us about the potential power consumption of a building without a photovoltaic system.

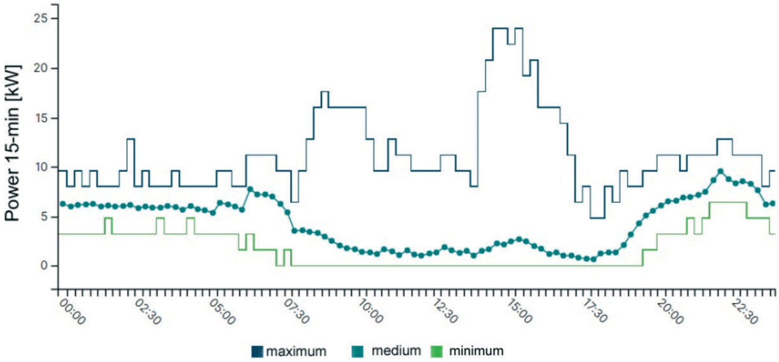


Fig. 3. 15-minute profile of active power drawn from the Onemeter app

At the end of such analyses, the authors assume that the annual consumption of the building itself is the same as the annual energy consumption of an electric vehicle.

2.3. Proposed photovoltaic system solutions

Based on previous analyzes and calculations, it was established that the annual energy demand of an electric vehicle is 4,100 kWh and the same is the demand of our building. So we need about 10,000 kWh of electricity per year. The surplus results from prosumer settlements with the energy distributor and seller (old rules) or unfavorable results of the purchase and sale of energy on the energy exchange (new rules).

To generate this amount of energy in our location (Poland, Lublin), an installation with a peak power of approx. 10 kWp is needed. Where to get the actual information to support this assumption? Just go to the website of the manufacturer of photovoltaic inverters (https://monitoringpublic.solaredge.com/) and review the performance of several photovoltaic systems in our area [36]. It has been confirmed that the 9.6 kWp plant is able to produce more than 10,000 kWh per year (see Figure 4).

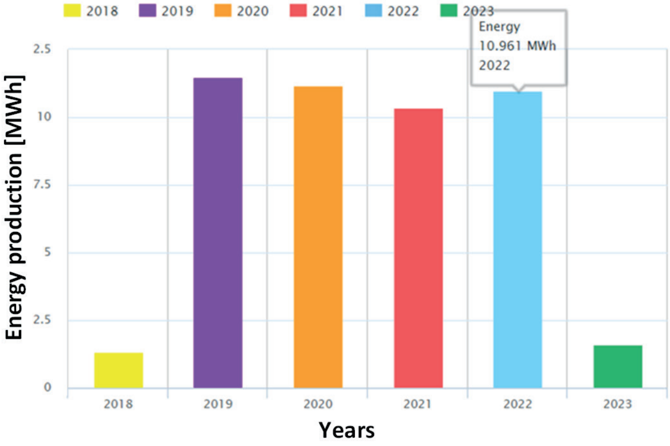


Fig. 4. Annual energy production by an installation with a peak power of 9.6 kWh

The photovoltaic installation with a peak power of 10 kWp currently consists of 20 panels with dimensions of 1 x 2 m. It can be installed on the roof of the building (Figure 5), on the ground (Figure 6 in the background) or on a carport creating a carport (Figure 6 in the foreground). The construction of such carports is complex and requires the constructor to take into account many factors affecting the strength of the structure and the amount of energy produced [18].

Fig. 5. Photovoltaic installation placed on the roof of a residential building

Fig. 6. Photovoltaic installation in the form of a carport (foreground) and placed on the ground (second plan)

3. Analytical confirmation of the assumptions of the size of the photovoltaic installation for the selected electric vehicle

In this part of the article, the use of the Metalog family of distributions to predict the electricity production of a photovoltaic system with the accuracy of a probability distribution will be presented. The amount of electricity produced by the carport on particular days of the month will be used to determine the Cumulative Distribution Functions (CDF). It is a continuous function. Then the Probability Density Function (PDF) was determined. The Metalog family of distributions allows you to make calculations for a specific photovoltaic carport located in a specific location (Lublin in Poland) and in a specific context (location on the ground, azimuth, shading). The Metalog family of distributions allows to determine the percentiles [19] in the production of electricity by a photovoltaic carport and the answer what its value will be with the accuracy of the probability distribution. The Metalog approach talks about the composition of probability distributions. It is a complex distribution [20].

In this part of the article, the probability of generating more power than needed to charge the specified number of traction batteries per month and per day by a real photovoltaic installation with a peak power of 9.6 kWp will be calculated.

Let us now reverse the calculations made at the end of Section 2.1 and present the results in tabular form (Table 1).

Tab. 1. Vehicle mileage and energy needed

	Mileage [km]	Energy needed [kWh]
annual	30,000	4,100
monthly	2,500	342.6
daily	83.3	11.4

According to the authors, the most important thing is to confirm the monthly production of electricity needed to cover the assumed distance. Data on the amount of energy produced was obtained from the Internet platform as in Figure 4. The graph of the amount of energy produced in individual months of the year is shown in Figure 7. The data collected over the full 4 years shows that monthly production may vary significantly in individual years. This is, of course, the result of differences in insolation, cloudiness, temperature and amount of precipitation. However, the obtained data can be the basis for statistical calculations.

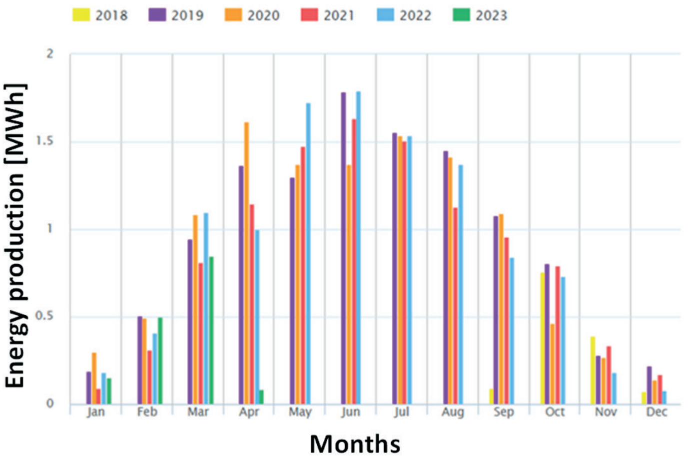
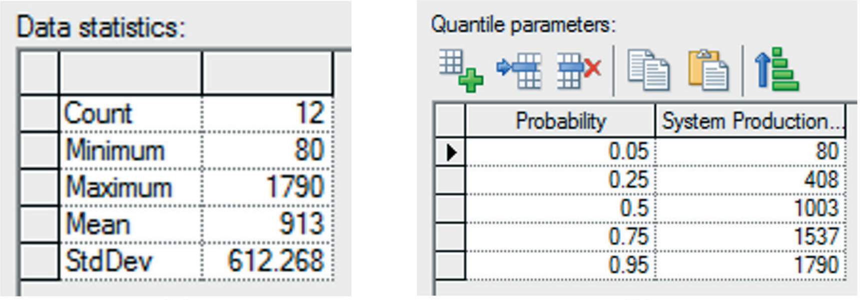


Fig. 7. Monthly energy production by an installation with a peak power of 9.6 kWh

The GeNIe 4.0 Academic software has built-in Metalog distribution families and allows to quickly determine the Cumulative Distribution Function, the Probability Density Function and an easy way to extract information from the knowledge base.

The Metalog family of distributions allows for a more advanced statistical analysis, including the determination of quantiles, as shown in Figure 8. The analysis was based on the monthly energy production in 2022 only by the tested photovoltaic installation.



Data statistics:

Count	12
Minimum	80
Maximum	1790
Mean	913
StdDev	612.268

Quantile parameters:

Probability	System Production...
0.05	80
0.25	408
0.5	1003
0.75	1537
0.95	1790

(a) (b)

Fig. 8. Basic statistics; (a) and more advanced statistics including determination of quantiles (b) for monthly energy production in 2022

Then, the Cumulative Distribution Function (Figure 9) and the Probability Density Function (Figure 10) were determined.

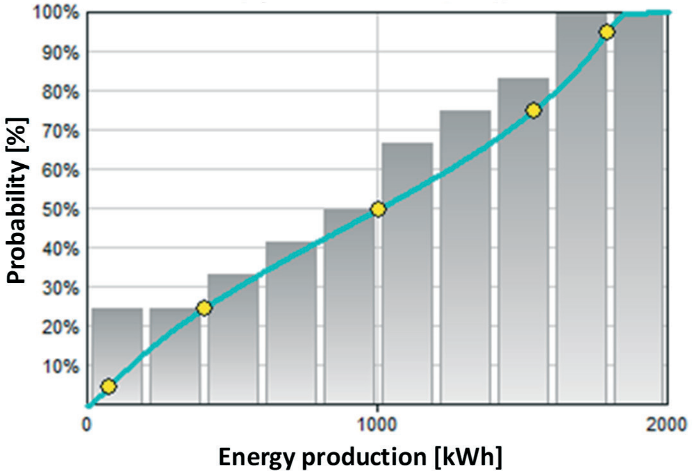


Fig. 9. Cumulative Distribution Function for energy produced by a photovoltaic installation in individual months of 2022

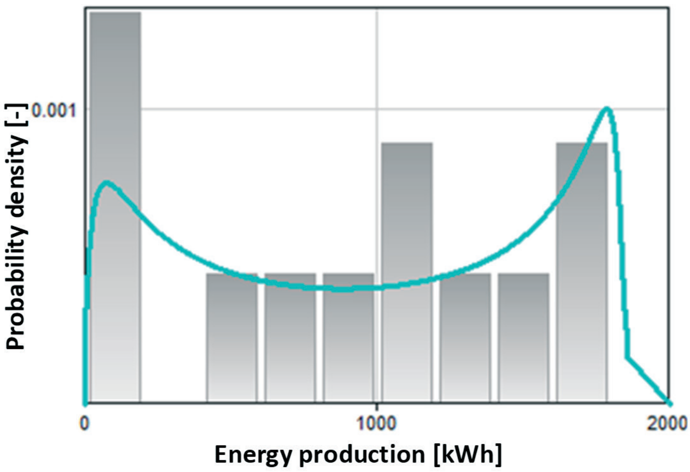
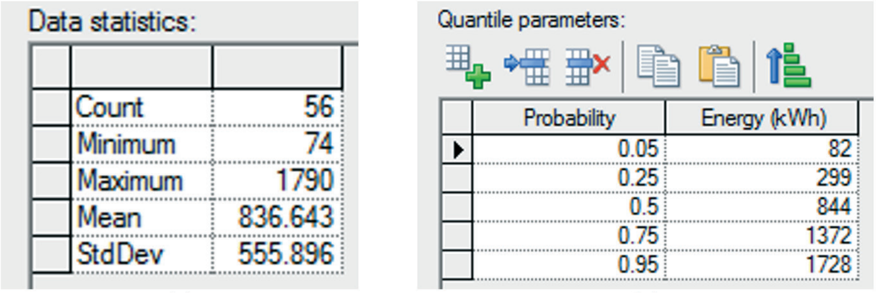


Fig. 10. Probability Density Function for the energy produced by the photovoltaic installation in individual months of 2022

The next step to increase the accuracy of the calculations was to determine the Cumulative Distribution Function and the Probability Density Function for the energy produced by the photovoltaic installation in individual months throughout its operation. And as before, work began with basic and more advanced statistics, which are presented in Figure 11.


Data statistics:

Count	56
Minimum	74
Maximum	1790
Mean	836.643
StdDev	555.896

Quantile parameters:

Probability	Energy (kWh)
0.05	82
0.25	299
0.5	844
0.75	1372
0.95	1728

(a) (b)

Fig. 11. Basic statistics; (a) and more advanced statistics including determining quantiles (b) for monthly energy production over the lifetime of the photovoltaic installation

The GeNIe 4.0 Academic software makes it possible to determine the Cumulative Distribution Function and the Probability Density Function for various k factors as shown in Figure 12.

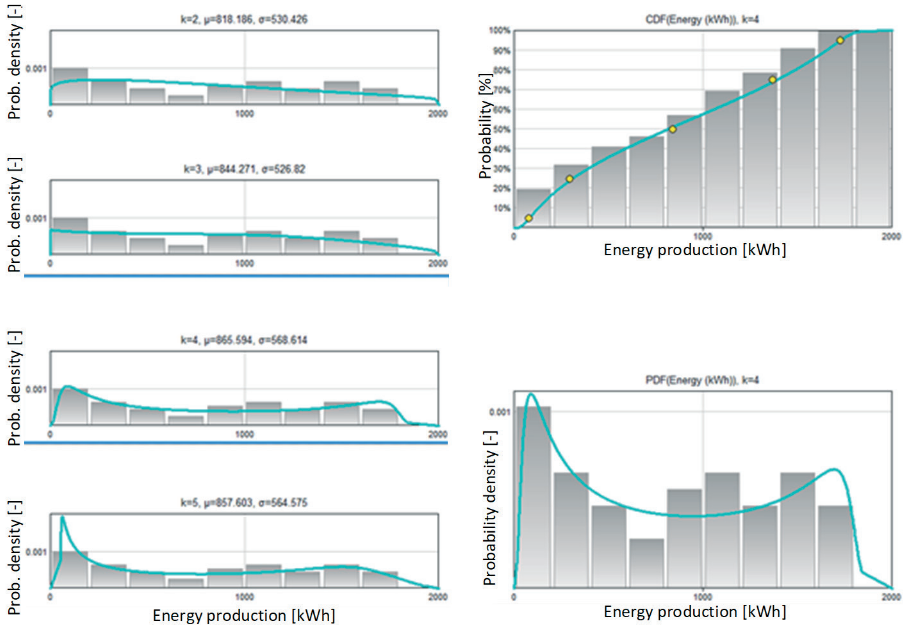


Fig. 12. Cumulative Distribution Function and Probability Density Function for energy produced monthly by a photovoltaic installation in individual months throughout the period of operation, divided into 10 ranges

The measurement data used for calculations can be divided into 10 (as in Figure 12) or more ranges. Figure 13 presents the Cumulative Distribution Function and the Probability Density Function for the energy produced monthly by the photovoltaic installation in individual months throughout the period of operation, divided into 20 ranges. The data obtained are identical in both cases. Only the measuring points were assigned to 20 and not to 10 measuring ranges.

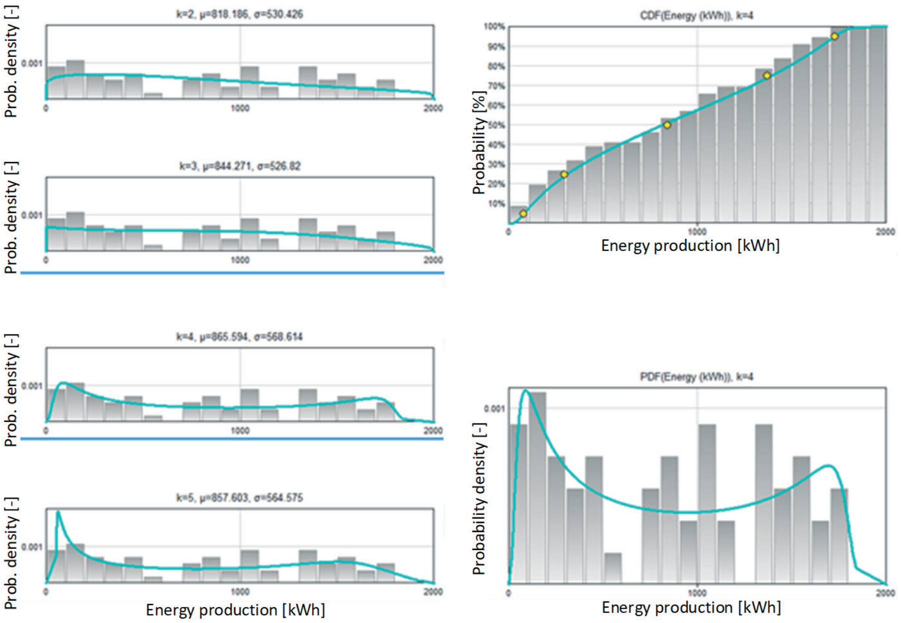
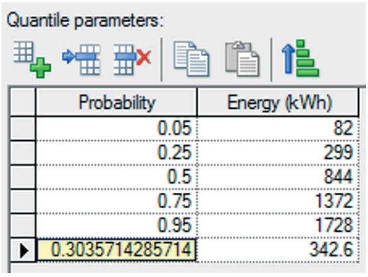


Fig. 13. Cumulative Distribution Function and Probability Density Function for energy produced monthly by a photovoltaic installation in individual months throughout the period of operation, divided into 20 ranges

The last step is to get the information from the knowledge base. We calculate the probability of monthly energy production by the photovoltaic installation of 342.6 kWh (figure 14).


Quantile parameters:

Probability	Energy (kWh)
0.05	82
0.25	299
0.5	844
0.75	1372
0.95	1728
0.3035714285714	342.6

Fig. 14. Probability of monthly electricity production equal to or less than 342.6 kWh by the PV system during its lifetime

The program's answer to the question asked is as follows: The probability of a monthly production of electricity equal to or less than 342.6 kWh by the photovoltaic system during the entire period of its operation is 0.3035. So the probability of producing more than 342.6 kWh is 1–0.3035. The obtained probability value of 0.6965 is high enough to assess the monthly energy production of a photovoltaic installation with a peak power of 9.6 kWp as sufficient to supply electricity to a Renault Zoe electric vehicle with a battery with an energy capacity of 41 kWh and to cover a monthly distance of 2,500 km.

4. Conclusions

Based on many years of practice in the use and charging of electric vehicles, as well as their diagnostics, servicing and repair, the authors have developed an algorithm for selecting the power of a photovoltaic installation for an electric vehicle.

The authors have made a detailed description of the electric vehicle and other electrical receivers that will be powered by energy from a home photovoltaic installation. A scientific approach to the archiving and processing of measurement data obtained from various sources is presented.

The presented approach related to the use of the Metalog distribution family can be used to simulate various strategies for generating energy by photovoltaic systems depending on the energy demand for charging the selected electric vehicle (characterized by the energy capacity of the battery). It is worth emphasizing once again that the presented calculations are made for a specific photovoltaic installation in a given location and in a specific context (e.g. time).

From the results presented above, it can be concluded that the daily amount of energy produced is very important in the selection of the power of the photovoltaic installation for charging the selected electric vehicle. Another important time period to be considered, subject to statistical analysis, is the monthly amount of energy produced. Individual users and people managing fleets of electric vehicles very often summarize the amount of energy consumed and pay for it on a monthly basis.

The algorithm proposed by the authors was used to assume the peak power of the photovoltaic installation. This assumption was then confirmed analytically by using the Metalog family of distributions. The obtained probability value of 0.6965 is high enough to assess the monthly energy production of a photovoltaic installation with a peak power of 9.6 kWp as sufficient to supply electricity to a Renault Zoe electric vehicle with a battery with an energy capacity of 41 kWh and to cover a monthly distance of 2,500 km.

The authors intend to continue research in the field of energy generation by photovoltaic systems and its storage in stationary energy storage for charging electric vehicles. Energy storage is getting cheaper and allows to increase the amount of energy produced from RES for own needs (self-consumption).

5. Nomenclature

BEV	battery electric vehicles
BLDC	brushless direct current motor
BMS	battery management system
CDF	cumulative distribution function
CNG	compressed natural gas
DC	direct current
EV	electric vehicles
LPG	liquefied petroleum gas
PDF	probability density function
PMAM	permanent magnet asynchronous motor
PMSM	permanent magnet synchronous motor
PV	photovoltaic
RES	renewable energy sources

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