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# THE SELECTION OF AN ELECTRIC VEHICLE FOR THE EXISTING PHOTOVOLTAIC SYSTEM – CASE STUDY IN POLISH CLIMATIC CONDITIONS

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## Abstract

The article presents an algorithm for selecting an electric vehicle for your photovoltaic system. Generating electricity by distributed photovoltaic systems is a very visible trend across Europe. Individual and institutional owners are looking for opportunities to save large amounts of money spent on the purchase of electricity. Many times they have built a photovoltaic system larger than their current energy needs. The author suggests a solution to increase the energy produced for own needs instead of giving it to the power grid at unfavourable prices. Such a solution is the purchase of an electric vehicle that will be charged with surplus energy. Research on the selection of a vehicle for a photovoltaic system should start with a precise profile of the current energy consumption from the power grid, energy production from the photovoltaic system and transferring its excess to the power grid. The next step is to characterise the potential electric vehicle. Such characteristics include the determination of the energy capacity of the traction battery and the methods of its charging. The final stage is the analytical confirmation of the choice made. For this purpose, the Metalog family of distributions was used to determine the probability of generating the appropriate hourly amount of energy needed to charge an electric vehicle.

**Keywords:** electric vehicle; photovoltaic system; energy overproduction; battery charging

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# 1. Introduction

Generating electricity by distributed photovoltaic systems is a very visible trend across Europe. Individual and institutional owners are looking for opportunities to save large amounts of money spent on the purchase of electricity. The investment in your own photovoltaic system pays off after just a few years of operation. If the investment is not co-financed from any sources, the payback time for such an investment in Poland is currently about five years. Obtaining subsidies for the implemented system may shorten the payback time to approx. three years. After this time, the owner can generate certain amounts of energy and not pay for them at all. How long can this state last? It can be determined based on the approximate lifetime of the solar panels used. It is usually 25 years.

Lubelskie Voivodship is the sunniest region in Poland. An photovoltaic system with a peak power of 1 kWp can generate more than 1 MWh of electricity per year in these particular conditions [30].

Reducing the costs of photovoltaic systems was possible thanks to the intensive development of science and technology in this area. For many years, scientists have been working on new materials capable of converting solar radiation into usable electricity with increasing efficiency. Currently, intensive work is underway on the use of perovskites to build flexible photovoltaic modules that can be installed on any substrate [29]. Their potential application is the installation of panels on the roofs of vehicles, especially public transport buses. Materials engineering is of particular importance in the research and development of photovoltaic panels. Modern engineering materials used to build photovoltaic panels give them good current-voltage characteristics. In addition, they are fixed on a durable base and are resistant to changing weather conditions and various levels of precipitation. Recently, bifacial panels have become popular; these have an active surface on both sides of the panel [34]. Thus, they effectively use the back part of the energy reflected from the ground or other objects such as buildings. Thanks to this possibility, the power achieved from one bifacial panel is much higher than traditional one-sided panels produced in poly and monocrystalline technology.

Regarding the characteristics of photovoltaic systems, it is necessary to mention photovoltaic inverters. At present, these are electronically controlled converters of direct current (DC) electricity produced by photovoltaic systems into single or three-phase alternating current (AC) present in the power grid [33].

Photovoltaic systems are increasingly using stationary energy storage [45]. This is the result of the decreasing prices of such warehouses. Energy storage facilities can be charged with energy that is surplus to the current demand [4]. Hybrid inverters are used for these purposes [42]. They offer two types of electric current at their outputs: alternating and direct. AC receivers will be supplied with alternating current from the power grid. Direct current can

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be used to charge stationary energy storage systems and to charge electric vehicles without any losses. Energy storage facilities can also be charged with energy from the power grid. The owner can then use the attractively priced electricity tariffs to charge the stationary energy storage and use it during higher prices. Electric vehicles can also be a mobile form of energy storage. The constantly developing and increasingly popular Vehicle to Grid (V2G) technology allows you to store energy in the traction battery of the vehicle and give it back to the building at any time.

It is worth noting that almost all elements of such an energy ecosystem are Internet of Things devices [28]. They are capable of generating large amounts of data (big data), which can then be processed using artificial intelligence methods (data processing) and used for diagnostic purposes or to manage electricity [13].

Electric vehicles have many advantages over vehicles powered by combustion engines [18]. They are quiet, accelerate dynamically [49] and do not emit any pollutants into the atmosphere where they are used [5]. An increasing number of customers are buying electric vehicles because of their ecology [6, 10]. The origin of electricity intended for charging electric cars is very important. For ecological reasons, the best solution is to use energy from renewable energy sources (RES) to charge electric vehicles. Due to their quiet operation and zero emission, electric drives are used to power passenger cars, buses [31], floating ships and drones [25].

Electric vehicles need large amounts of electricity to cover long distances [24, 46]. A compact passenger car needs approximately 15 kWh of energy to travel 100 km [14]. Modern DC chargers designed for charging electric vehicle batteries have powers of up to 350 kW [9]. Taking large amounts of energy from the grid at very high power levels can cause problems [2, 15]. Therefore, charging large fleets of electric vehicles in particular should be carried out according to established strategies [8, 17]. Electric vehicles can also play a positive role in balancing electricity from renewable energy sources [1]. Large amounts of electricity generated, especially at midday, increasingly cannot be stored in the power grid. This excess energy can be used to charge electric vehicle batteries [37]. Modern vehicle batteries are currently able to store from 70 kWh to even 100 kWh of energy [12]. This amount of energy ensures a range of electric vehicles of over 500 km [35]. To cover shorter distances, ranging from several to several kilometers, customers choose electric vehicles other than cars. These include bicycles and scooters [21].

Therefore, electric vehicle batteries can constitute high-capacity mobile energy storage. Charging vehicles with excess electricity generated by photovoltaic systems or wind farms also has an economic impact [40]. This energy is relatively cheap compared to normal prices for energy purchased from the power grid. Therefore, many owners of photovoltaic systems in Poland and around the world also purchase stationary energy storage facilities and/or electric vehicles. This approach allows you to maintain a certain level of energy independ-

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ence [32]. Customer behaviour in the area of electromobility should continue to be studied using sociological tools. The motivations of electric vehicle buyers are not yet well understood [3, 44]. Ecological vehicle drives should be promoted and state governments should apply subsidies to the purchase of electric vehicles [20]. People who are afraid to buy an electric vehicle often buy hybrid vehicles [11].

Photovoltaic systems are increasingly being built in the form of carports. This approach allows you to save space for building a ground-based photovoltaic system [19]. In addition, carports generate shade for the electric vehicle while it is charging. Such solutions are very popular in countries with hot climate and lots of sunlight [26]. Electromobility is a big challenge for local governments [27] and entire countries [43]. In particular, it is about ensuring an adequate number of chargers for electric vehicles and sufficient electricity [36]. Proper charging infrastructure for electric vehicles, including both fast and slow charging points, can contribute to a faster spread of electric vehicles in a given region [48, 38]. Providing electric vehicles with the appropriate level of service is also a huge challenge especially when it concerns traction batteries [1]. The structure of individual components in electric vehicles differs significantly from those used in vehicles with combustion engines [7].

## 2. Characteristics of photovoltaic system

Owners of photovoltaic systems, wanting to become independent from the energy drawn from the power grid, have often built photovoltaic systems larger than their current energy demand. The author suggests a solution to increase the energy produced for own needs instead of giving it to the power grid at unfavourable prices. Such a solution is the purchase of an electric vehicle that will be charged with surplus energy. Research on the selection of a vehicle for a photovoltaic system should start with a detailed profile of the current energy consumption from the power grid, the production of energy from the photovoltaic system and the transfer of its excess to the power grid. The object of the research is a ground system with a capacity of up to 40 kWp built at the Lublin Science and Technology Park. The appearance of the system is shown in Figure 1. The system consists of 142 polycrystalline panels. The photovoltaic system is directed exactly south and the angle of inclination of the photovoltaic panels is 40 degrees. A three-phase inverter with a power of 40 kW converts and transfers the energy produced to the building of the Lublin Science and Technology Park (LSTP). Excess energy not used for own needs is transferred to the power grid.

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**Fig. 1. Appearance of a ground-based photovoltaic system with a peak power of 40 kWp**

Figure 2 shows the amount of energy produced annually since its start-up. The amount of energy produced in 2023 takes into account its production from the beginning of the year to November 22. The presented data shows that, in fact, a 40 kWp system is able to generate over 40,000 kWh of electricity in specific climatic conditions. This data was obtained from the online platform of the manufacturer of inverters for photovoltaic systems [16]. Measurement and diagnostic data packages are sent to the cloud server every few minutes. The photovoltaic system administrator has access to them. You can freely display them in the form of reports as well as download and process them for scientific purposes.

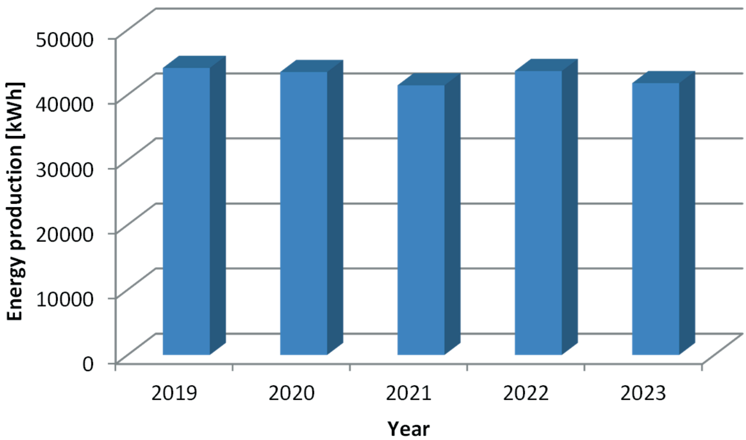


**Fig. 2. Annual amounts of energy produced by a 40 kWp photovoltaic system**

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A 40 kWp photovoltaic system supplies electricity to Segment 5 of the LSTP building. There are mainly offices and research laboratories that work on weekdays. Analysing the hourly profile of electricity consumption on a weekday (Figure 3), we can see that from 1.00 to 7.00, the building consumes an average of approx. 9 kW of power. At 8.00 the value of the consumed power starts to increase and remains at an elevated level until 17.00. In the evening, the average power consumption is approx. 10 kW. On this autumn day, the photovoltaic system produced a small amount of energy and this was omitted from the considerations. Measurement data from a bidirectional energy meter were obtained using an Internet of Things device in the form of a beacon [39].

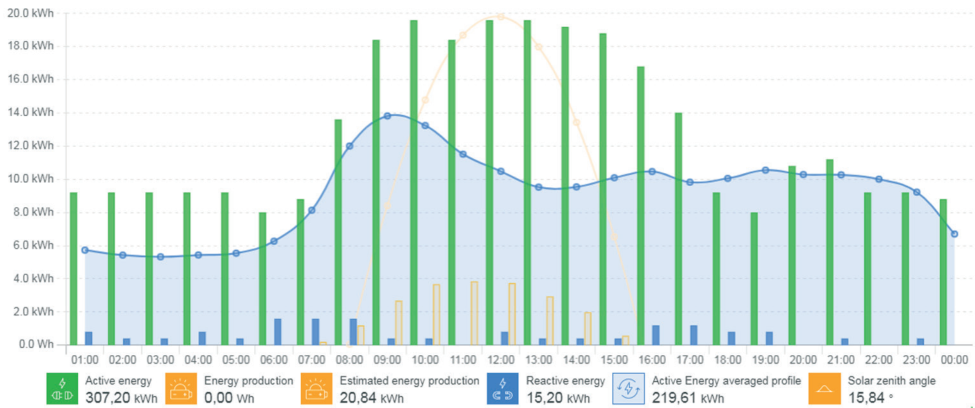


**Fig. 3. Hourly energy charts on December 12, 2021 (Friday)**

In September 2021, the LSTP building downloaded 3.5 MWh of electricity from the power grid and gave back 1.8 MWh of energy that was not used for its own needs. The large amount of energy fed into the grid prompted the owner to make more detailed analyses. It turned out that a very large amount of unused energy is produced during the weekend. The lack of tenants in the building translates into small amounts of energy being needed. As is clearly visible in Figures 4 and 5, the energy generated by the photovoltaic system is able to cover the energy demand of the building and, moreover, large amounts of it are transferred to the power grid. The excess power produced is up to 27 kW which gives energy of 27 kWh per hour.

On Saturday, 4 September 2021, the LSTP building downloaded 72.8 kWh of electricity from the power grid (Figure 4). At the same time, 171.2 kWh of energy produced by the photovoltaic system and not used by the LSTP building was transferred to the power grid.

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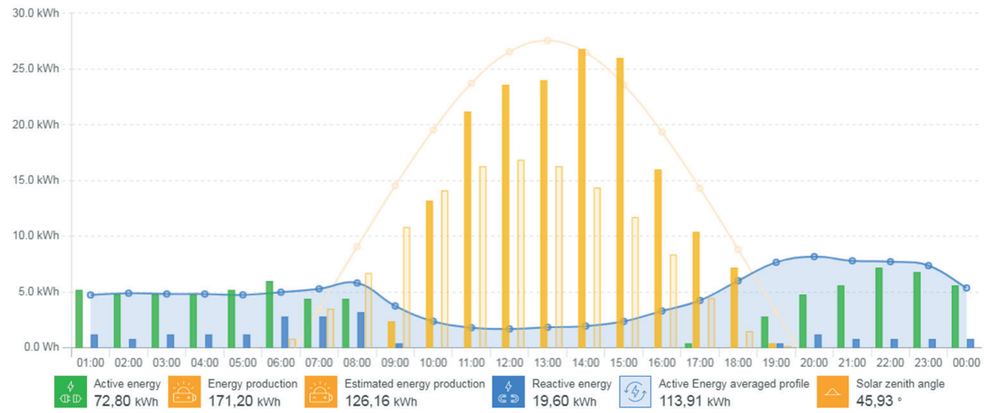


**Fig. 4. Hourly Energy Charts on September 4, 2021 (Saturday)**

On Sunday, 5 September 2021, the LSTP building downloaded 72.4 kWh of electricity from the power grid (Figure 5). At the same time, 168 kWh of energy produced by the photovoltaic system and not used by the LSTP building was transferred to the power grid. A thorough analysis of the collected data confirmed that for almost all weekends, there are very large amounts of energy fed into the power grid.

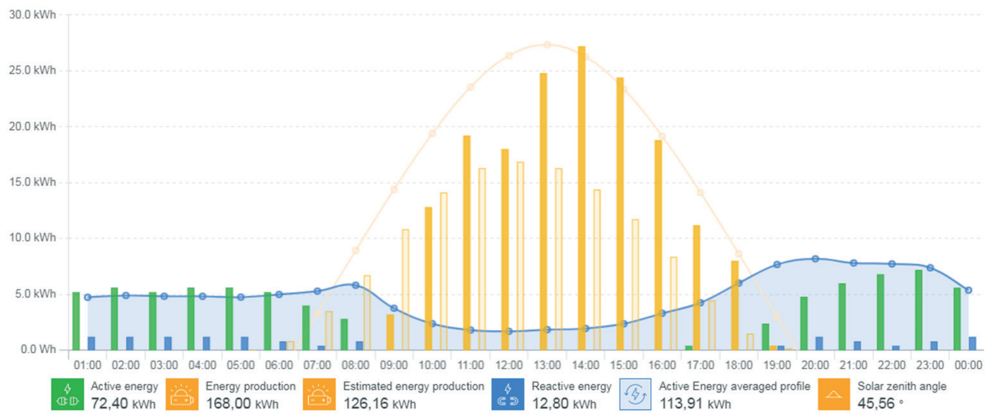


**Fig. 5. Hourly energy charts on September 5, 2021 (Sunday)**

The supervisor/manager of the photovoltaic system proposed that the energy not used for the building's own needs should be used to charge electric cars. Another option, of course, was to sell this energy to an electricity sales company at a very low price.

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## 3. Characteristics of a potential electric vehicle

The next step is to characterise a potential electric vehicle that could be charged from the energy produced by the photovoltaic system. Such characteristics include the determination of the energy capacity of the traction battery of the vehicle and the methods of its charging. The VW ID.4 electric vehicle produced in 2022 was selected for the tests.

The battery of the VW ID.4 has an energy capacity of 77 kWh. It gives the city SUV a WLTP range of up to 549 km. The battery can be charged using the Type 2 connector with a power of 11 kW. The charging time for a completely empty battery is 7 hours. This was confirmed when charging using our charger connected to the photovoltaic system. The second way to charge the battery is fast charging with a power of up to 125 kW, within 30 minutes it will provide the energy needed to drive 320 km [47]. More parameters of the electric drive system of the VW ID.4 are presented in Table 1.

**Tab. 1. Parameters of the electric drive of the VW ID.4 vehicle**

| | Parameter |
|---|---|
| Electric motor maximum power | 150 kW |
| Acceleration 0–100 km/h | 8,5 s |
| Energy capacity of the traction battery | 77 kWh |
| Battery charging socket | CCS, Type 2 |
| Maximum AC charging power | 11 kW |
| Maximum DC charging power | 125 kW |
| Energy consumption | 14 kWh/100 km |
| Total range (WLTP) | 549 km |

By charging an electric car only once a week on a weekend day, we gain the ability to drive about 500 km in real mixed driving conditions (urban and extra-urban cycle) from the excess energy produced by the system. This gives about 2,000 km per month. The authors' experience shows that the photovoltaic system is able to produce larger amounts of energy in Polish geographical and climatic conditions for 8 months a year (from March to October). A simple calculation shows that a range of 16,000 km can be ensured in this way.

## 4. A practical solution to the problem

The authors proposed and implemented a practical solution to the defined problem. A charging pole with a maximum power of 22 kW was added to the existing 40 kWp system. The selection of the power of the charging post resulted from the excess power produced by the photovoltaic system, as shown in Figure 3. The charging post in question has two sockets for charging electric vehicles: Type 2 (AC 3-phase 400 V) and Schuko (AC 1-phase 230 V). The

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charging post has a panel to start and end the charging process and a magnetic card reader based on which, access to the charger is verified. On the display, the customer can choose the language of operation and read the charging time and the amount of energy consumed. The appearance of the test charging post is shown in Figure 6.


**Fig. 6. Appearance of a research charging pole with a maximum power of 22 kW connected to a photovoltaic system**

The graph in Figure 7 shows the hourly overproduction of energy, the energy needed to charge the VW ID.4 vehicle and the energy consumed taken from the power grid. The latter was consumed when the excess energy was not able to cover the vehicle's energy requirement for charging the battery. The overproduction after charging is the result of subtracting the overproduction of energy before charging and the energy for charging. We can see that this is a significant amount of energy, which would almost be enough to charge another similar vehicle.

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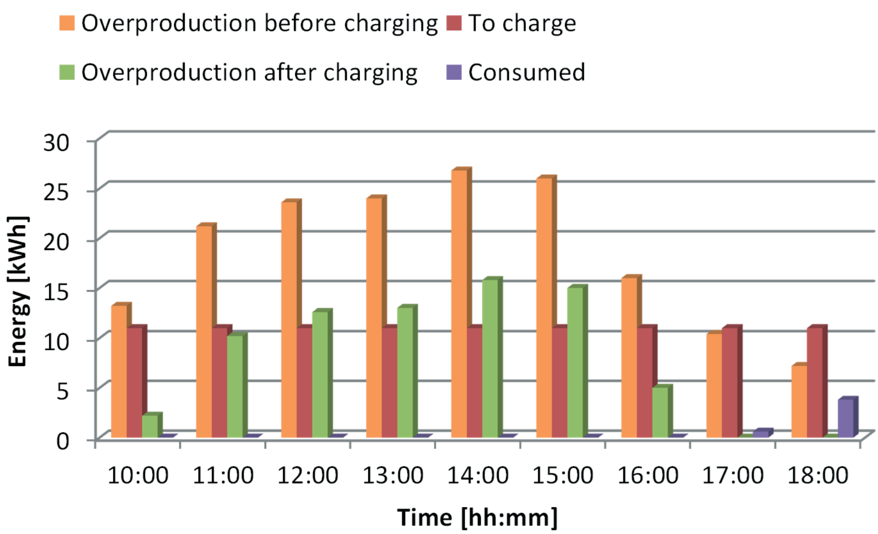


**Fig. 7. Energy graphs during operation of the photovoltaic system and charging of the electric vehicle**

## 5. Analytical confirmation of the correct selection of an electric vehicle for a photovoltaic system

The final stage is the analytical confirmation of the choice made. For this purpose, the Metalog family of distributions was used to determine the probability of generating the appropriate hourly energy needed to charge an electric vehicle.

Using the Metalog family of distributions, we obtain information from a knowledge base, not from a database [23]. 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 inverse function of the empirical distribution distribution [22].

In their research, the authors used the GeNIe 4.0 Academic version. It has built-in families of Metalog distributions that allow you to quickly determine the empirical distribution distribution, the probability density function and a simple way of obtaining information from the knowledge base. So far, the authors have used the Metalog family of probability distributions for the selection of a photovoltaic carport power for an electric vehicle [41].

The Metalog family of distributions allows for more advanced statistical analysis, including the determination of quantiles. The results of calculations for energy constituting overproduction on 4 September 2021 are shown in Figure 8. Measurement data from nine hours of operation of the photovoltaic system from 9.00 to 18.00 were taken into account for the calculations.

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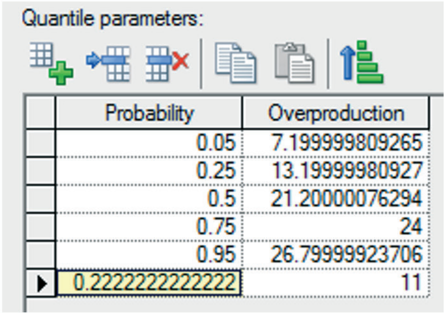
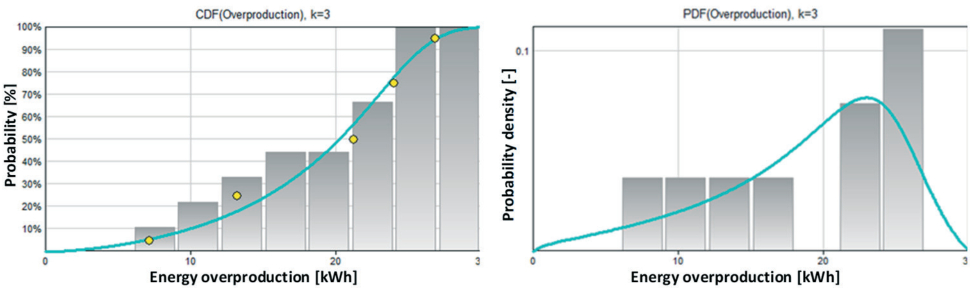


Quantile parameters:

| Probability | Overproduction |
|---|---|
| 0.05 | 7.199999809265 |
| 0.25 | 13.19999980927 |
| 0.5 | 21.20000076294 |
| 0.75 | 24 |
| 0.95 | 26.7999923706 |
| 0.2222222222222 | 11 |

**Fig. 8. Quantile parameters for overproduction of energy on 4 September 2021**

The next step was to determine the cumulative distribution function (Figure 9a) and the probability density function (Figure 9b).




(a) (b)

**Fig. 9. Metalog family of distributions calculation results; (a) cumulative distribution function for energy overproduction on 4 September 2021, (b) probability density function for energy overproduction on September 4, 2021**

The next step is to obtain information from the knowledge base. We calculate the probability of an hourly overproduction of energy of 11 kWh during nine hours of operation of the photovoltaic system. The probability of an hourly overproduction of electricity equal to or less than 11 kWh by the PV system on 4 September 2021 is 0.2222 (see the last row in the table in Figure 8). Thus, the probability of an hourly overproduction of more than 11 kWh is 1–0.2222=0.7778. It is very likely, but will it allow you to fully charge the empty battery of the VW ID.4 electric vehicle with a capacity of 77 kWh? The calculated probability allows you to count on obtaining the total energy for charging the vehicle of 0.7778*9*11 kWh=77 kWh. Thus, it was possible to fully charge the battery of an electric vehicle with surplus energy.

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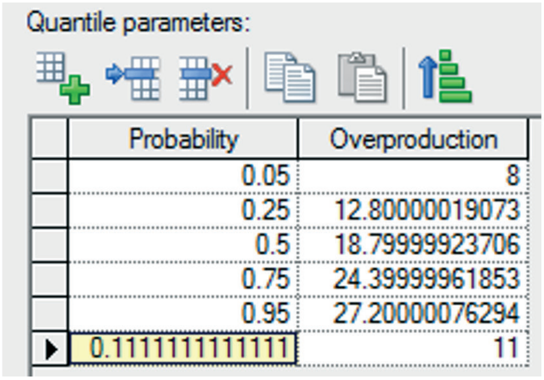
Identical calculations were carried out for the overproduction of energy on the next day of the weekend – 5 September 2021. The results of the calculation of the quantile parameters for the overproduction energy on 5 September 2021 are shown in Figure 10. The calculations also included measurement data from nine hours of operation of the photovoltaic system from 9.00 to 18.00.


Quantile parameters:

| | Probability | Overproduction |
|---|---|---|
| | 0.05 | 8 |
| | 0.25 | 12.80000019073 |
| | 0.5 | 18.79999923706 |
| | 0.75 | 24.39999961853 |
| | 0.95 | 27.20000076294 |
| ▶ | 0.11111111111111 | 11 |

**Fig. 10. Quantile parameters for overproduction of energy on 5 September 2021**

The next step was to determine the cumulative distribution function (Figure 11a) and the probability density function (Figure 11b), as in the previous case.

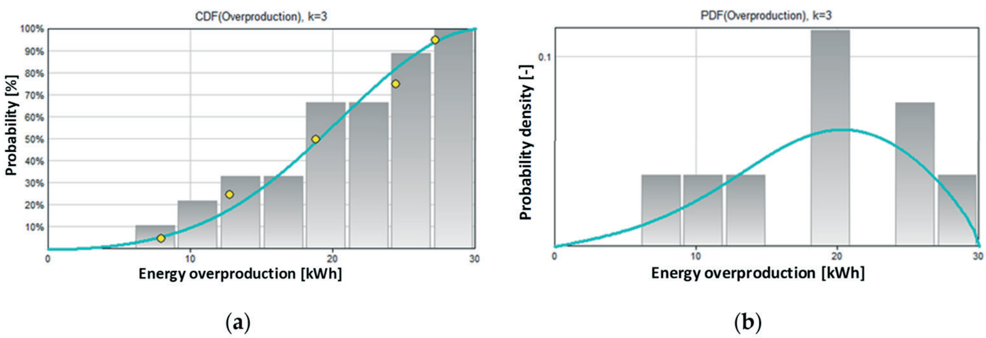



**Fig. 11. Metalog family of distributionscalculation results; (a) cumulative distribution function for energy overproduction on 5 September 2021, (b) probability density function for energy overproduction on 5 September 2021**

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The next step was also to obtain information from the knowledge base. We calculate the probability of an hourly overproduction of energy of 11 kWh over nine hours of operation of the photovoltaic system. The probability of an hourly overproduction of electricity equal to or less than 11 kWh by the PV system on 5 September 2021 is 0.1111 (see the last slot in the table in Figure 10). Thus, the probability of an hourly overproduction of more than 11 kWh is 1–0.1111=0.8889. It is very likely, but will it allow you to fully charge the empty battery of the VW ID.4 electric vehicle with a capacity of 77 kWh? The calculated probability allows you to count on obtaining the total energy for charging the vehicle of 0.8889*9*11 kWh=88 kWh. Thus, it was also possible to fully charge the battery of the electric vehicle with surplus energy on the next day of the weekend.

Weather conditions do not always ensure the possibility of fully charging the vehicle's battery in one day of the weekend. For our purposes, it is enough that the probability of producing excess energy over the two days of the weekend is enough to ensure that the battery of the electric vehicle is fully charged. Consider another day, which, however, is characterised by a much smaller hourly overproduction of electricity (Figure 12).

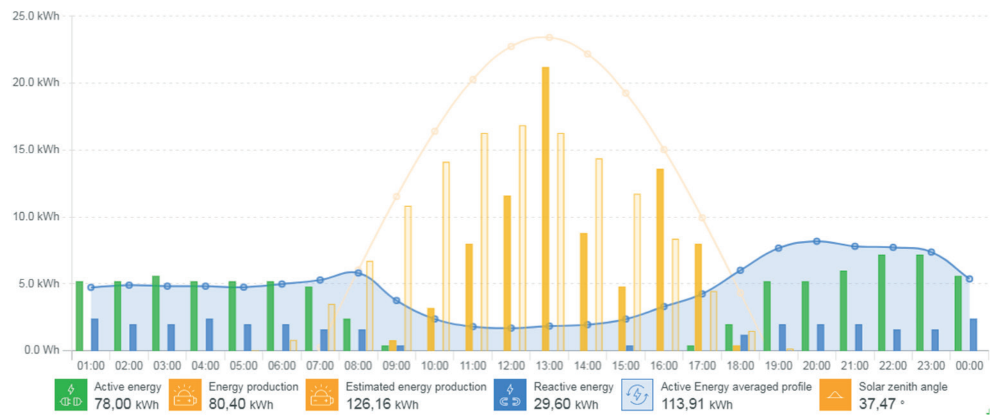


**Fig. 12. Hourly energy charts on September 26, 2021 (Sunday)**

Identical calculations as presented above were carried out for overproduction of energy on September 26, 2021. The results of the calculation of the quantile parameters for the overproduction energy on 26 September 2021 are shown in Figure 13. The calculations also included measurement data from nine hours of operation of the photovoltaic system from 9.00 to 18.00.

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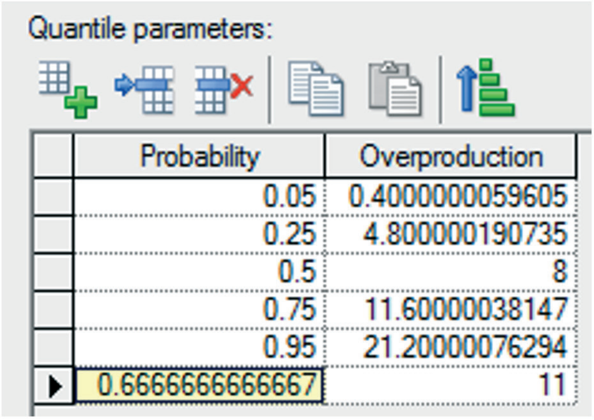
Quantile parameters:

| | Probability | Overproduction |
|---|---|---|
| | 0.05 | 0.4000000059605 |
| | 0.25 | 4.800000190735 |
| | 0.5 | 8 |
| | 0.75 | 11.60000038147 |
| | 0.95 | 21.20000076294 |
| ▶ | 0.6666666666667 | 11 |

**Fig. 13. Quantile parameters for overproduction of energy on 26 September 2021**

The next step, as in the two previous calculation cases, was to determine the cumulative distribution function (Figure 14a) and the probability density function (Figure 14b).

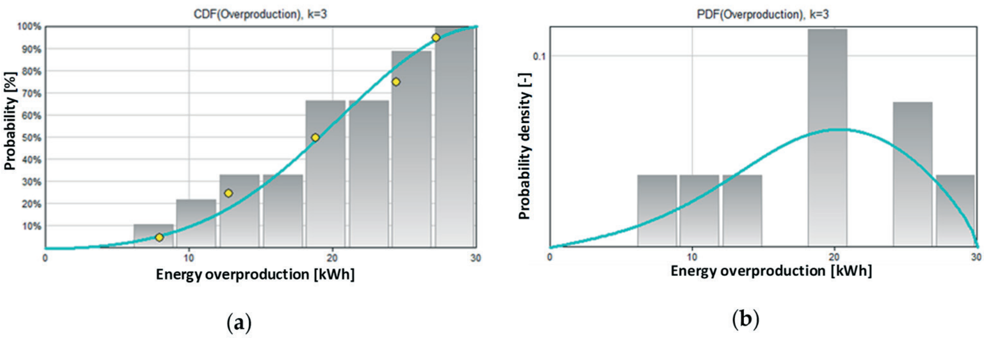


**Fig. 14. Metalog family of distributions calculation results; (a) cumulative distribution function for energy overproduction on 26 September 2021, (b) probability density function for energy overproduction on 26 September 2021**

The next step was to obtain information from the knowledge base. We calculate the probability of an hourly overproduction of energy of 11 kWh over nine hours of operation of the photovoltaic system. The probability of an hourly overproduction of electricity equal to or less than 11 kWh by the PV system on September 26, 2021 is 0.6666 (see the last row in the table in Figure 12). Thus, the probability of an hourly overproduction of more than 11 kWh is 1–0.6666=0.3334. It is very unlikely, but will it allow you to fully charge an empty VW ID.4 electric vehicle with a capacity of 77 kWh? The calculated probability allows you to count on

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obtaining the total energy for charging the vehicle of 0.3334*9*11 kWh=33.01 kWh. Thus, it was not possible to fully charge the battery of an electric vehicle with only the energy that was surplus on that day. The missing energy will be taken from the power grid, which will negatively affect the cost of charging the electric vehicle.

## 6. Conclusions

Administering a platform that monitors the performance of the photovoltaic system and energy consumption by the building and the transfer of excess energy to the distribution network allows you to collect large amounts of measurement data in the cloud server. Data obtained from IoT devices can be displayed and processed to manage electricity.

The authors proposed an algorithm for selecting an electric vehicle for the existing photovoltaic system. In the case of a photovoltaic system with a peak power of 40 kWp, almost all of the energy produced on weekdays was used for self-consumption (self-consumption). The monitoring system allowed us to notice that large amounts of energy were fed into the power grid, especially on weekends, when there were no tenants in the LSTP building. The authors proposed to charge an electric vehicle from the excess energy produced. On the basis of the hourly overproduction energy, the charger power that an electric vehicle should have was determined. The amount of energy returned to the grid during one or two weekend days should also be greater than the energy capacity of the battery of the selected vehicle.

The last stage of the research was the analytical confirmation of the choice made. For this purpose, the Metalog family of distributions was used to determine the probability of generating the appropriate hourly energy needed to charge an electric vehicle. The approach related to the use of the Metalog distribution family presented in the article can be used to simulate various strategies for generating energy by photovoltaic systems depending on the energy demand for charging the selected electric vehicle (characterised by the power of the on-board charger). It is worth noting that the presented calculations are made for a specific photovoltaic system in a given location and in a specific context (e.g. time). The performed calculations confirmed the validity of the assumptions in two out of two analysed cases. It is worth emphasising that September days were selected for the analysis, when energy production by photovoltaic systems is not the highest.

Charging electric vehicles with energy coming from a photovoltaic system and exceeding the building's own needs is the most economical and ecological method of charging. The proposed method of using the Metalog family of probability distributions can be practically used in the algorithms of energy management systems in buildings that have chargers for electric vehicles.

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# 7. Acknowledgement

The paper submitted for the first time for publication in our periodical will be treated as an original. After the peer reviews are received, all changes to the paper should only be made in the "Track changes" mode.

# 8. Nomenclature

| | |
|---|---|
| AC | alternating current |
| BEV | battery electric vehicles |
| CDF | cumulative distribution function |
| DC | direct current |
| LSTP | Lublin Science and Technology Park |
| PDF | probability density function |
| PV | photovoltaic |
| RES | renewable energy sources |

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