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Strategic Model for Charging a Fleet of Electric Vehicles with Energy from Renewable Energy Sources

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Abstract: The ever-growing number of electric vehicles requires increasing amounts of energy to charge their traction batteries. Electric vehicles are the most ecological when the energy for charging them comes from renewable energy sources. Obtaining electricity from renewable sources such as photovoltaic systems is also a way to reduce the operating costs of an electric vehicle. However, to produce cheap electricity from renewable energy sources, you first need to invest in the construction of a photovoltaic system. The article presents a strategic model for charging a fleet of electric vehicles with energy from photovoltaic systems. The model is useful for sizing a planned photovoltaic system to the energy needs of a vehicle fleet. It uses the Metalog family of probability distributions to determine the probability of producing a given amount of energy needed to power electric vehicle chargers. Using the model, it is possible to determine the percentage of energy from photovoltaic systems in the total energy needed to charge a vehicle fleet. The research was carried out on real data from an operating photovoltaic system with a peak power of 50 kWp. The approach presented in the strategic model takes into account the geographical and climatic context related to the location of the photovoltaic system. The model can be used for various renewable energy sources and different sizes of vehicle fleets with different electricity demands to charge their batteries. The presented model can be used to manage the energy produced both at the design stage of the photovoltaic system and during its operation.

Keywords: electric vehicles; traction batteries; battery charging; renewable energy sources; artificial intelligence

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Citation: Caban, J.; Małek, A.; Šarkan, B. Strategic Model for Charging a Fleet of Electric Vehicles with Energy from Renewable Energy Sources. *Energies* **2024**, *17*, 1264. https://doi.org/10.3390/en17051264

Academic Editor: Quanqing Yu

Received: 16 February 2024
Revised: 28 February 2024
Accepted: 3 March 2024
Published: 6 March 2024

1. Introduction

For over ten years, two trends have been visible in Poland, Europe, and around the world [1–3]. The first concerns the increasingly widespread use of electric vehicles. Every year, more electric vehicles appear on the streets, powered by electricity from a traction battery on board the vehicle [4–8]. The second trend is the generation of electricity from renewable energy sources (RES) [9–13]. Each of these trends was clearly visible in 2023 and a strong growth trend is observed in each of them for the following years. Electromobility and the production of energy from renewable energy sources have a very large impact on the environment and people's behavior. Each of these trends also causes problems that must be carefully examined to counteract them.

Electromobility began to develop dynamically after 2012, when large car companies such as Nissan, Renault, and Tesla began to introduce new models of electric cars to the market. Going back a dozen or so years, it must be admitted that they had a very short range and needed a very long time to charge the traction batteries with electricity.

The average range of an electric vehicle was approximately 100 km. An even greater challenge was the lack of public infrastructure for charging them. In Europe, and especially in Poland, it was almost impossible to find a fast charger with a power of 40 kW. Owners of electric cars also had a lot of problems due to different standards of plugs found in vehicles and chargers [14]. However, despite these difficulties, electric vehicles were gaining recognition among customers due to the advantages that distinguished them over traditional vehicles with combustion engines [15]. Such advantages include, above all, the high power of electric traction motors and the very convenient course of the torque as a function of rotational speed [16]. This meant that electric vehicles were and still are very dynamic, which is of great importance during urban driving [17]. When driving around the city in an electric vehicle, you should also notice and appreciate that there is no need to change gears. The high power and torque available from zero rotational speed to very high rotational speeds guarantee high vehicle acceleration and flexibility. Electric motors are also quiet and more trouble-free than combustion engines [18]. The quiet operation of the vehicle's engine is of great importance both for the driver, for pedestrians moving near the vehicles, and also for residents, especially in cities. The scope of operation and service activities for electric cars is much smaller, which translates into lower costs of warranty and post-warranty inspections at vehicle service stations. Electric vehicles are also ecological at the point of use because they do not emit any harmful substances into the atmosphere [19–21]. The most ecological form of propulsion for all types of vehicles is electric drive, using electricity generated from RES to charge the battery.

At the beginning of 2024, we have a completely different situation in Poland, Europe, and the world. There are over 30 million vehicles on the road [22]. Electric vehicle batteries have an energy capacity that allows them to travel over 400 km on a single charge. The development achieved during the last decade was possible thanks to numerous research and development works carried out at universities and research institutes [23–27] and automotive concerns. There is a well-developed infrastructure for charging electric vehicle batteries throughout Europe [28]. It includes 7, 11, and 22 kW AC (alternating current) supply poles for electric vehicle on-board chargers. They are used to slowly charge vehicle batteries during longer periods of parking at home, at work, and in public places. The number of chargers charging vehicle batteries with DC (direct current) with power ranging from 40 to 250 kW is also constantly growing. Currently, the fastest DC chargers have a power of 350 kW and are able to charge electric vehicle batteries in 15 min [29]. Such chargers are usually located at gas stations and passenger service areas located on highways and expressways. Thanks to them, it is possible to travel freely in an electric vehicle throughout Europe. Scientists in research institutes and engineers in large automotive companies are improving technologies for wirelessly charging batteries in vehicles [30]. Owners of electric vehicles can use applications on mobile devices and those built into the vehicle to plan an electric vehicle route, including battery charging points. Thanks to high competition in the automotive industry, especially from American and Chinese manufacturers, the prices of electric cars are decreasing, and they are becoming available to an increasing number of people. The development of electromobility is also supported by various types of government incentives and other forms of subsidies for owners of electric vehicles. In this area, it is worth presenting the proposals available in Slovakia [31,32] or Romania [33] and Scandinavian countries [34,35].

Tens of millions of electric vehicles require very large amounts of electricity to power them. And this is where new technologies in the field of RES come to the rescue. In Europe and around the world, the most popular among them are photovoltaic systems (PV) capable of producing electricity from solar radiation and wind turbine systems that convert kinetic energy of winds into electricity. Driving on the highway through European countries, you can easily see large ground-mounted photovoltaic systems with an area of several hectares, generating peak powers of several MWp. They consist of thousands of individual panels made using monocrystalline technology. The newest of them produce electricity using both sides of the panel and are called bifacial panels. The landscape of large photovoltaic systems is often complemented by wind turbines over 200 m high, which already have a capacity of over 3 MW each. Both of these RES are characterized by periodicity and variability in the amount of energy produced. Photovoltaic systems produce electricity only during the day when the sun is shining. Wind turbines produce energy only when the wind blows.

Therefore, the best solution is to charge electric vehicles with energy from a mix of energy generated using PV systems and wind turbines. Then, only a small amount of energy would come from the power grid and would come from burning fossil fuels such as coal. This would occur when the sun is not shining and the wind is not blowing. However, investments in renewable energy technologies pose many challenges [36]. One of them is the capacity of the power grid [37]. At times of high sunlight, high wind, and low demand for power received from the power grid, the voltage in the network may increase above the permissible voltage in order to protect electrical receivers. This involves turning off the inverters and deactivating the fans. People who invested in renewable energy will not only not earn any money but will also have to pay extra for supplying energy to the grid at such times [38]. Such moments may therefore be an opportunity to charge the batteries of electric vehicles with very cheap electricity, which will reduce the costs of individual and collective transport [39,40].

The aim of the article is to create a strategic model for charging electric vehicles with energy from RES in the form of ground-based PV systems. Archived data on the daily amount of energy produced by a ground-based PV system with a peak power of 40 kWp will be used for this purpose. These will then be processed using the Metalog family of probability distributions to model daily electricity production. Then, knowledge about the expected amount of electricity produced will be obtained from the knowledge base in the form of a mathematical model, accurate to the probability distribution.

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 [41], mathematics [42], and electronics [43]. The authors have already used Metalog probability distribution families to select the peak power of a photovoltaic carport for an electric vehicle [44].

The research presented in the article may be helpful to renewable energy developers who plan to build new generating capacity to power large fleets of electric vehicles [45]. They can also be helpful to private individuals or local governments that have problems with balancing the energy network in larger or smaller areas [46]. Large numbers of electric vehicles with traction batteries with high energy capacity may be helpful for this purpose. Electric buses with batteries with a capacity of over 200 kWh and passenger vehicles with batteries with a capacity of up to 100 kWh can be charged with DC chargers with adjustable output power [47]. This solution is also helpful for owners of PV systems who have built a system with too much power and are unable to use the energy produced. The solution to this problem is to purchase an electric vehicle with a battery with an appropriate energy capacity.

2. Research Methodology

The authors proposed to use the Metalog family of probability distributions to determine electricity production. Using this method, it is possible to determine the amount of energy produced on a daily, monthly, or yearly basis with accuracy to the probability distribution [48]. The amount of electricity produced on individual days of the month by a roof-based photovoltaic system with a peak power of 50 kWp will be used to determine the cumulative distribution function (CDF). This is a continuous function. Then, the probability distribution function will be determined. The authors used GeNIe 4.1 Academic software for calculations. It 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 [49]. The Metalog approach used in the software provides a lot of information about the composition of probability distributions [50]. Using the Metalog family of distributions, it is possible to obtain information from a knowledge base and not from a database. In a database, answers to questions are obtained by searching the database, while a knowledge base answers questions by running an inference algorithm, which is a fundamental difference.

3. Characteristics of Energy Production from Photovoltaic Systems in Poland (City of Lublin)

When making conceptual assumptions regarding the size of the photovoltaic system for charging vehicle batteries, the owner of the vehicle fleet should take into account the geographical and climatic context related to the location of the photovoltaic system. It is common knowledge that the expected amount of energy produced depends primarily on the location of the system and its location on the ground or on the roof of the building. There are also special photovoltaic structures called carports, which also protect the vehicle against excessive heating by the sun [40]. The peak power and the type of photovoltaic panels used have a significant impact on the amount of energy produced. In 2024, monocrystalline panels are used almost exclusively, and wherever justified, the bifacial version is used. Panels installed on the ground and in carports can then also generate electricity through the lower part of the panels [51]. In this way, the amount of energy produced from the same unit of surface increases. The azimuth and angle of inclination of the panels are also important. The place intended for a photovoltaic system should not be permanently or temporarily shaded by buildings or trees. Climatic factors also influence the amount of energy produced. Local cloud cover and windy conditions significantly affect the amount of energy produced by photovoltaic systems that are close to each other.

The European Commission collects, monitors, and makes available databases enabling the determination of the amount of electricity produced monthly by photovoltaic systems located in various places in Europe. It was decided to check the operation of such an online platform. The results obtained from it may be important in the preliminary determination of monthly amounts of energy produced for charging a fleet of electric vehicles.

A photovoltaic system located in the Lublin Voivodeship was selected for research under Polish geographical and climatic conditions. It is worth emphasizing that it has the best sunshine in Poland. The intensity of solar radiation is, of course, different in individual regions of Poland and ranges from 900 kWh/m^2 to 1200 kWh/m^2. In order to determine the properties of a photovoltaic system mounted on a roof and located in Poland, in the specific city of Lublin, the above-mentioned Internet platform was used. It is based on a database of installations from various European countries. It allows you to generate the properties of a photovoltaic system connected to the power grid and export data in the form of charts or in csv format. The platform allows you to generate the performance of a photovoltaic system with a specific peak power, taking the following into account:

- Geographic location;
- System installation locations (ground, roof);
- Photovoltaic panel technology;
- Start the system;
- The angle of inclination of the panels;
- Azimuth.

The appearance of the Internet platform window for determining the properties of a photovoltaic system is shown in Figure 1.

The results obtained from the Internet platform allow for a preliminary estimate of the amount of energy produced by a photovoltaic system with specific power and design parameters located in a specific geographical context. However, based on the results presented in Figure 2, it can be clearly stated that the amount of energy produced per month varies significantly depending on the month of production, i.e., on the seasonality of the seasons.

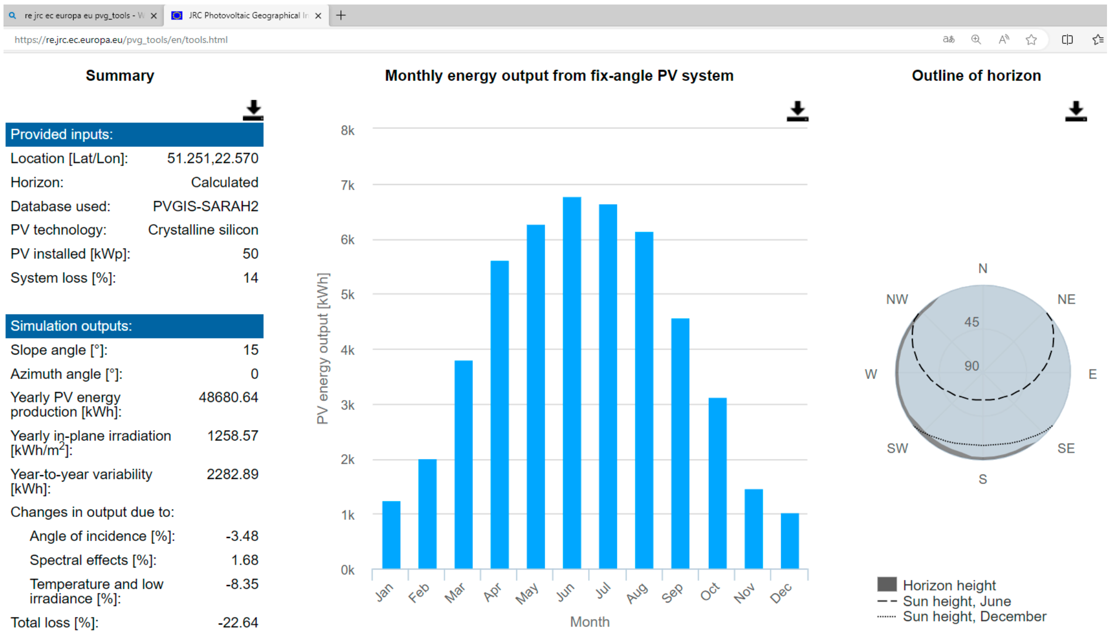

Figure 1. Properties of a photovoltaic system with a peak power of 50 kWp connected to the power grid located in Poland in the city of Lublin.

The amounts of monthly energy production by a photovoltaic system with a peak power of 50 kWp located in Poland in the city of Lublin are shown in Figure 2.

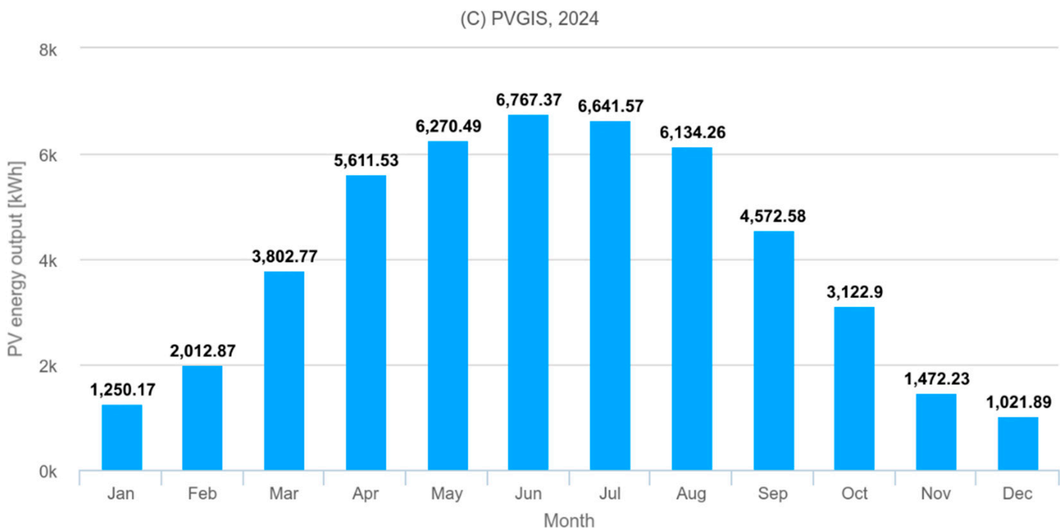

Figure 2. Amounts of monthly energy production by a photovoltaic system with a peak power of 50 kWp located in Poland in the city of Lublin.

4. Case Study of Electricity Production for Charging a Vehicle Fleet

4.1. Characteristics of the Photovoltaic System

The authors of this article have many years of experience in monitoring the performance and management of photovoltaic systems. This experience gives rise to an approach to modeling the amount of energy produced. Trends currently visible in the market include the installation of panels on flat roofs of institutional and corporate buildings. Photovoltaic panels are then mounted on structures not permanently attached to the roof at much smaller angles of inclination. Also, the direction of installation of the panels is not oriented towards the south. An increasing number of individual and institutional investors have decided to orient their panels to the east and west. Eastern orientation allows you to maximize the amount of energy produced in the morning. The western orientation allows you to maximize the amount of energy produced in the afternoon. Both the east and west orientation of the panels are characterized by less energy produced at high noon. Due to the large amount of energy produced by photovoltaic systems at high noon and their lack of reception, excessive voltage increases in the power grid very often occur. Grid balancing problems lead to individual photovoltaic inverters being turned off to protect the loads. This means the idle operation of the entire system or several photovoltaic systems in the area until the voltage in the network drops.

The research used a photovoltaic system located on the roof of the Lublin WSEI Academy (Figure 3). The panels were mounted at an angle of 15°, azimuth 295°. The appearance of the photovoltaic system is shown in Figure 3. The photovoltaic system produced over 45 MWh of energy in 2023. The most efficient month in terms of energy production from this photovoltaic system was May when the system produced 7.7 MWh. The amount of energy produced on individual days of May 2023 is shown in Figure 4. The system produced a similar amount of energy (7.5 MWh) in July. Due to Polish geographical and climatic conditions, there are favorable conditions for the production of electricity only in selected months of the year. Monthly amounts of energy produced from a photovoltaic system with a peak power of 50 kWp higher than 2 MWh can be counted on in the months from March to October. In the autumn and winter months from November to February, energy production in Polish geographical and climatic conditions is very low.

Figure 3. Appearance of a photovoltaic system with a peak power of 50 kWp placed on the roof of a university building.

Much more information than the monthly energy production by the photovoltaic system is provided by the amount of energy produced on individual days of the month. The month with the highest energy production can be used to determine the maximum daily amount of energy produced. As we can see in Figure 4, a 50 kWh system is able to produce over 300,000 Wh or 300 kWh per day.

The authors specifically selected a PV system with a peak power of 50 kWp for the study. This is the maximum power value for micro-installations that can be built in Poland by individual users and companies. Contrary to appearances, the energy produced in one day from such an installation can power quite a large fleet of vehicles. Let us use examples of electric vehicles from the Renault family. One of the authors is the owner of an electric vehicle Renault Twizy, which has a traction battery with a capacity of 6 kWh. The Renault Kangoo small delivery vehicle has a traction battery with a capacity of

45 kWh. The Renault Zoe, one of the best-selling vehicles in Europe at the time, had batteries with a capacity of 22 kWh at the beginning of production and then 41 kWh. The Renault Megane E Tech car is a five-seater electric SUV. It has a battery with a capacity of 40 and 60 kWh to choose from. However, the large Renault Master delivery vehicle has a traction battery with a capacity of 40 or 87 kWh. Therefore, the energy produced during one day of work can be used to charge several to a dozen or so vehicles from zero to full. There are, of course, vehicles with large battery capacities. An example would be a Tesla model S with a battery capacity of over 100 kWh or an Audi e-tron GT with a capacity of over 90 kWh. Electric buses often have sets of traction batteries with a total energy capacity of over 200 kWh. For the latter vehicle fleets, PV systems with much higher peak powers should be considered than those presented by the authors in this article.

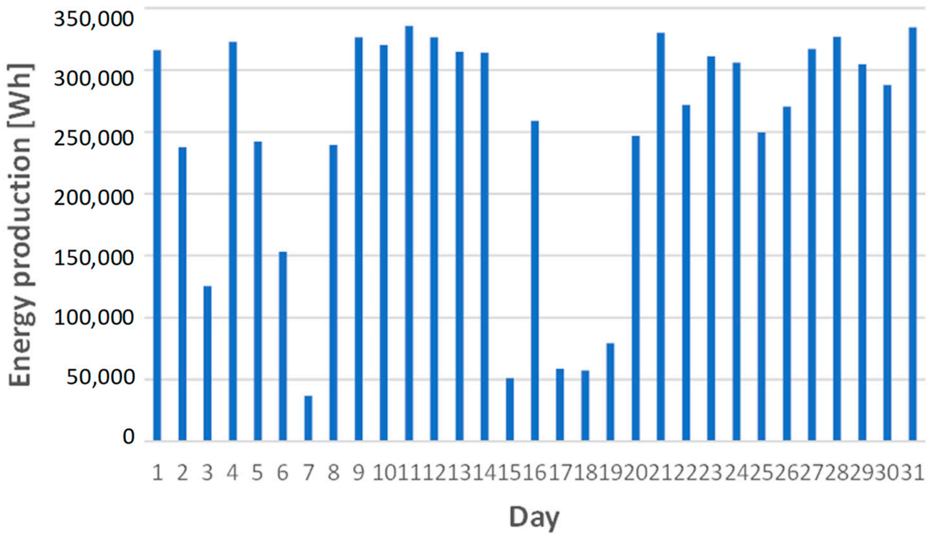

Figure 4. Appearance of amounts of daily energy production by a photovoltaic system with a peak power of 50 kWp in May 2023.

4.2. Charging a Fleet of Vehicles from Renewable Energy Sources

Many people question the real ecology of electric vehicles [20]. When their batteries are charged with electricity generated in coal-fired power plants, they are not actually emission-free vehicles. They are emission-free vehicles only at the point of use because they do not produce any harmful exhaust gases while driving. However, their emissions have been shifted from the exhaust pipe to the power plant. This fact is important in the context of smog and other undesirable phenomena occurring especially in cities. Electric vehicles are the most ecological when the energy for charging their traction batteries comes from renewable energy sources.

An amount of 300 kWh is the energy needed to fully charge four batteries of compact class electric vehicles. They are able to transport five people over a distance of over 2000 km. It is also equivalent to 150% of the energy capacity of the traction battery of an electric city bus. This can transport approximately 75 people over a distance of 300 km. Therefore, even a small photovoltaic system is able to produce significant amounts of energy, which enables the charged vehicle fleet to cover considerable distances.

On-board chargers mounted in vehicles or external chargers are used to charge vehicle traction batteries. The former are mobile converters of three-phase AC power supplied to the vehicle into the direct current needed to charge the lithium-ion battery packs of the vehicles. The latter are stationary devices supplying DC to vehicle traction batteries. Charging poles or wall boxes that provide AC power to charge vehicles typically have a power of 7, 11, or a maximum of 22 kW and are called slow battery charging systems. Stationary DC chargers have powers ranging from 10 to 350 kW. DC chargers with powers from 50 kW are called fast battery charging systems. When using a DC charger, the battery charging power depends on the power of the charger and the maximum power that can be charged [52]. The press report shows that the latest electric Porsche Taycan has a battery with a capacity of 105 kWh, which can be charged with a power of 320 kW [53]. Of course, the battery charging power can be and is limited by the BMS battery management system, but also by the charger itself and its operator [23]. This last function allows for a very broad control of the vehicle battery charging process. The amount of energy needed to charge a vehicle's battery can be delivered faster using high power or more slowly using lower power. The daily energy resource generated from renewable energy sources can also be distributed among many vehicles. Vehicle batteries can always be fully charged (state of charge, SoC = 100%) or quickly recharged to SoC = 80%. This is the limit value of the SoC allowing charging at maximum power. Further charging (from SoC = 80 to 100) takes place at lower power in order to protect the battery and extend the time of its proper functioning. There are, of course, also battery types that can be charged with higher power across a wider range of SoCs. Such batteries include lithium–titanium oxide (LTO) batteries. The maximum charging and discharging rate for them is 10C [54]. LTO-based batteries also have a wider operating temperature range and charging efficiency exceeding 98%.

The information presented above shows that the manager of an electric vehicle fleet can make various choices regarding the size of batteries in vehicles and the methods of charging them. Very often, one vehicle can be charged using both alternating current and direct current. This is made possible by combined charging system (CCS) sockets and connectors.

Therefore, the biggest challenge is to provide an adequate amount of energy from renewable sources to charge the batteries of the vehicle fleet. The price of fuel plays a very large role in a vehicle's total cost of ownership (TCO). In the case of electric vehicles, this is the price paid per unit of energy. It may vary depending on the country and the source of the electricity itself. RES have undergone and continue to undergo intensive development in recent years, thanks to which the prices of components for the construction of PV systems have significantly decreased. The return on investment in a PV system in Poland is approximately 5 years without subsidies and less than 3 years in the case of subsidies for investments from European Union funds. These are the authors' own calculations based on investments in PV systems in the Lublin Science and Technology Park. This means nothing more than having an almost free source of electricity after the payback period. Manufacturers and companies that assemble PVc systems currently offer a 25-year warranty on the operation of the main system components such as PV panels.

It is therefore justified to invest in new renewable energy generation capacity in the form of photovoltaic systems dedicated specifically to charging fleets of electric vehicles. It is worth emphasizing, however, that energy from PV systems constitutes only part of the energy needed to charge vehicle batteries. Some of it must be taken from the power grid, and regardless of its source (RES or coal), it will usually be much more expensive than that produced by your own RES source [13]. Therefore, the task of the energy manager in a company with a fleet of electric vehicles will be to appropriately select the peak power of the photovoltaic system for the fleet of vehicles owned or planned to be purchased. It is worth taking into account the fact that the shortest payback period for investments in new renewable energy sources is characterized by investments with the highest auto-consumption rates. It means using as much energy as possible for your own needs. It is usually unprofitable to feed excess energy produced into the power grid. The authors propose selecting the appropriate peak power of the PV system to the energy demand of the vehicle fleet in a tailor-made approach. This is best illustrated with a specific example, which will be presented in the next chapter.

4.3. Modeling of Charging a Fleet of Electric Vehicles with Energy from Renewable Energy Sources

According to the authors, knowing the probability of producing a certain amount of energy from PV systems in one day is key information necessary to plan and implement a charging strategy for an electric vehicle fleet. The strategic model developed by the authors will help with this.

In the third decade of the 21st century, almost all inverters in photovoltaic systems are Internet of Things devices. This means that their work regarding the instantaneous power produced and the energy generated over time is constantly monitored, and data regarding the system's operation are sent at regular intervals via wired or wireless transmission methods to the data cloud. Then they can be processed, analyzed, and presented in the form of useful charts supporting decision-making processes (business intelligence) in the area of energy management.

Data on the monthly amount of energy produced were exported in digital form and processed using specialized GeNIe 4.1 Academic software. First, the authors made calculations for the month with the highest monthly energy production, i.e., May 2023 (Figure 4).

Basic and extended statistical calculations were made for the acquired data, as presented in Tables 1 and 2. The minimum value of energy produced monthly was 36,897 Wh, the maximum value was 335,693 Wh, and the average value of energy produced was 247,558 Wh, with a standard deviation of 98,471.7 Wh. These data show that the daily amount of electricity produced in Polish geographical conditions is characterized by high variability in the month of May. The Metalog family of distributions allows for more advanced statistical analysis including the determination of quantiles, as shown in Table 2.

Table 1. Statistical data on the amount of energy produced in the month of May (basic).

No.	Parameter	Value
1	Count	31
2	Minimum	36,897
3	Maximum	335,693
4	Mean	247,558
5	Std. Dev.	98,471.7

Table 2. Statistical data on the amount of energy produced in the month of May (extended).

No.	Probability	May
1	0.05	51,079
2	0.25	237,691
3	0.5	287,934
4	0.75	320,393
5	0.95	334,289
6	0.1612903225806	100,000
7	0.2258064516129	200,000

The GeNIe 4.0 Academic software allows you to determine the cumulative distribution function (CDF) and probability density function (PDF) for various k coefficients (Figure 5). The probability density function plot shows that high probability densities occur for large daily amounts of energy generated. Therefore, in the spring months in Polish geographical and climatic conditions, we can expect favorable conditions for the production of large amounts of energy despite the still-short days. According to the authors, low air temperature has a very large impact on the production of the largest amount of energy of the year in May. In summer months such as June, July and August, the sun is higher above the horizon and shines much longer, but at much higher daily temperatures, which negatively affects the amount of energy produced.

The next step in the analysis was to obtain information from the knowledge base. The probability of daily energy production of 100,000 and 200,000 Wh was determined.

Obtaining information from the knowledge base is achieved by asking questions; for example: What is the probability of monthly electricity production equal to or less than 100,000 Wh by a PV system with a peak power of 50 kWp located in Lublin, Poland? The question is asked by generating an additional row in the table shown in Table 2 and entering the number 100,000 in the right column. The system response is 0.1613.

Therefore, the probability of producing more than 100,000 Wh of energy per month is 1 − 0.1613 = 0.8387. Questions can also be formulated regarding the probability of the energy produced also amounting to 200,000 Wh. Therefore, the presented approach related to the use of the Metalog family of distributions can be used to simulate different energy generation strategies for PV systems depending on the energy demand to charge a fleet of electric vehicles. The results of the determined probability are presented in Table 3. The presented data show that in Polish geographical and climatic conditions, a system with a peak power of 50 kWp is likely to be able to produce amounts of electricity of 100,000 and 200,000 Wh per day.

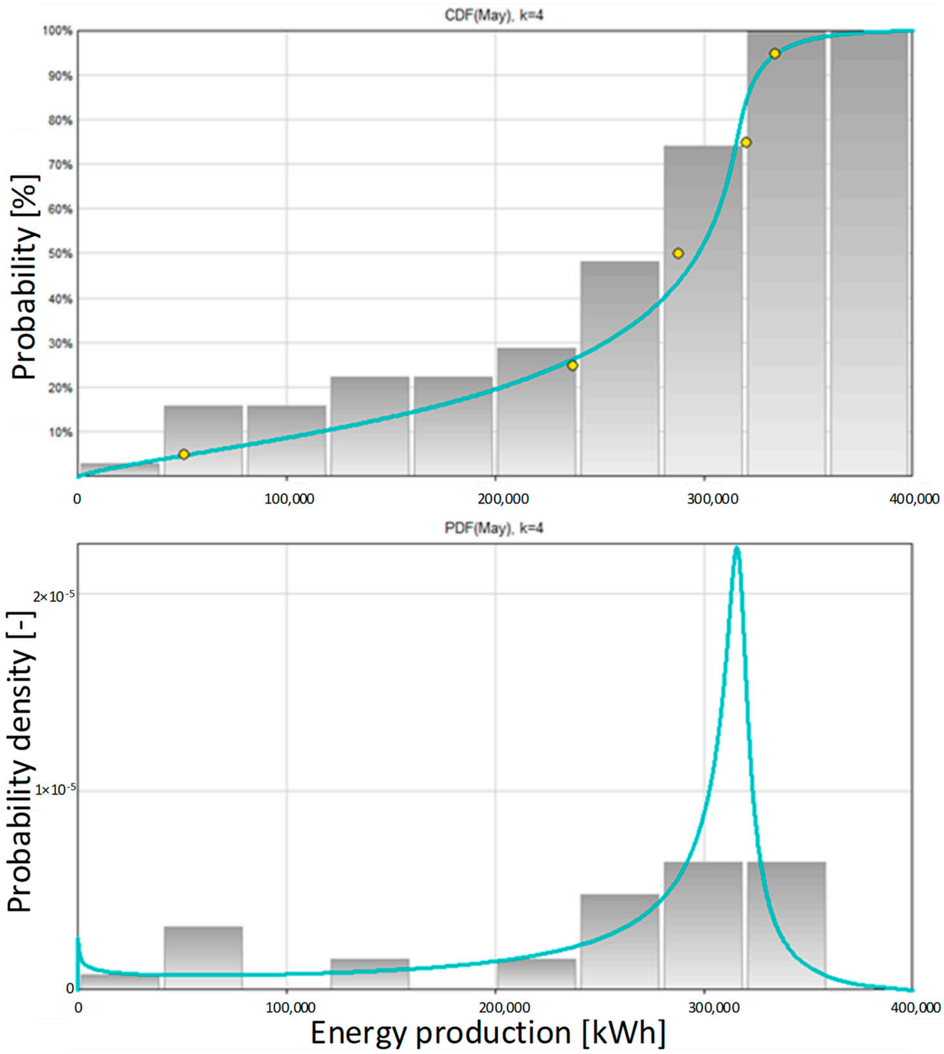

Figure 5. Cumulative distribution function (CDF) and probability density function (PDF) for energy produced by a 50 kWp photovoltaic installation in May 2023.

Table 3. Probability of the amount of energy produced by a 50 kWp PV installation located in Poland.

Energy [Wh]	Probability ≤	Probability >
100,000	0.1613	0.8387
200,000	0.2258	0.7742

The authors specifically proposed to take into account the amounts of energy produced per day of 100 and 200 kWh in the calculations. This is due to the fact that the month in 2023 with the highest energy production was analyzed. The basic statistical data presented in Table 1 show that the maximum value of energy produced per day this month exceeded 300 kWh. The authors recommend the use of stationary energy storage facilities in such situations. Energy from RES will soon also be used to produce hydrogen for storage and to power hydrogen fuel cell vehicles [21]. In this individual case, they propose using an energy storage with an energy capacity of 100 kWh. It is worth considering purchasing a new energy storage system using lithium iron phosphate technology (LFP) or giving new life to used traction batteries from electric vehicles. In the latter case, these will usually be lithium-ion batteries using NMC technology. An amount of 100 kWh is quite a large energy capacity and will involve a large investment outlay. Therefore, such an energy storage will not significantly reduce energy costs for electricity for charging electric vehicles, but it will increase auto-consumption of the produced energy and protect the renewable energy producer from additional fees for discharging energy into the grid at peak times. Moreover, it is an excellent solution to protect against voltage failures in the power grid (blackout). The proposed battery capacity is large enough to be 50% of the 200 kWh scenario and 100% of the 100 kWh scenario. The energy collected in the warehouse can be used to charge fleet vehicles in the evening or at night, i.e., when the photovoltaic system does not produce energy. The energy storage can also be used to charge vehicles the next day. Both the graph in Figure 4 and the course of the PDF in Figure 5 show that in the analyzed month of May, days with a large amount of energy produced are followed by days with a very small amount of energy produced. Therefore, energy storage gives the energy management manager the choice of charging source for electric vehicles from batteries or from the power grid. The energy storage also allows the vehicle fleet to be charged at night during periods of lower electricity prices (special energy tariffs) and discharged during periods of higher prices. The considerations presented above show that optimizing the process of charging a vehicle fleet is a complicated issue that requires a complex infrastructure for generating, storing, and transforming electricity. In this last area, it is worth mentioning hybrid inverters, which are able to convert DC produced in a PV system into the AC needed to power the power grid or into DC with the different voltages needed to charge an energy storage unit or charge a vehicle battery. Modern hybrid inverters are complex devices with many options for programming scenarios for charging and discharging energy storage.

In Polish geographical and climatic conditions, and taking into account the specific location context of the analyzed photovoltaic system, similar results were obtained for subsequent months of system operation. Figure 6 presents CDF and PDF for the energy produced by a 50 kWp photovoltaic installation in July 2023. The monthly energy production then amounted to 7.5 MWh. Expert analysis of the PDF provides information about the high density of the probability distribution in the range of large amounts of energy produced daily, ranging from 200 to over 300 kWh. However, the owner of a strategic model using the Metalog family of probability distributions and the previously mentioned GeNIe 4.1 Academic program does not have to have knowledge of the nuances of producing electricity from renewable energy sources; the owner can directly ask the knowledge base about the probability of producing a certain amount of energy in a given month.

To better understand how the strategic model of charging vehicles with renewable energy works, it is also worth considering the case of generating energy in months with lower amounts of energy produced. An interesting example to analyze is the daily energy production in October 2023. In Polish climatic and geographical conditions, it is the middle of autumn. Basic statistical analysis informs us that a photovoltaic system with a peak power of 50 kWp is able to produce over 100 kWh of energy in one day (Table 4). More advanced statistics already determine that this amount of energy produced falls within the probability percentiles of 0.75 and 0.95 (Table 5). By asking the knowledge base for the exact probability value (Table 5, last row), we obtain the answer that the probability of achieving a daily energy production of more than 100 kWh this month is $1 - 0.6774 = 0.3226$. The probability of producing a daily amount of energy greater than 200 kWh is 0.

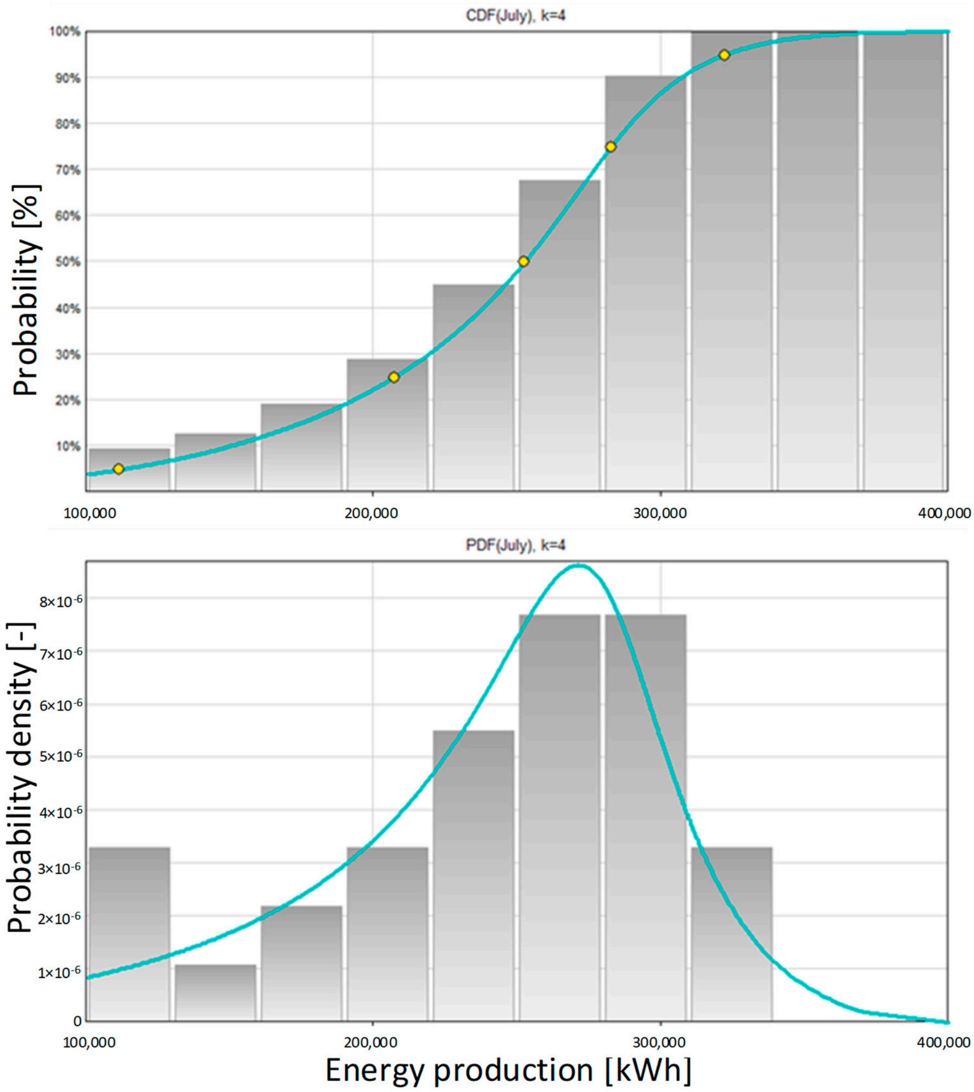

Figure 6. Cumulative distribution function (CDF) and probability density function (PDF) for energy produced by a 50 kWp photovoltaic installation in July 2023.

Table 4. Statistical data on the amount of energy produced in the month of October (basic).

No.	Parameter	Value
1	Count	31
2	Minimum	12,791
3	Maximum	139,447
4	Mean	78,951.5
5	Std. Dev.	36,056.3

Table 5. Statistical data on the amount of energy produced in the month of October (extended).

No.	Probability	October
1	0.05	23,052
2	0.25	49,366
3	0.5	82,626
4	0.75	112,014
5	0.95	133,549
6	0.6774193548387	100,000

Both the advanced statistical data presented in Table 5 and the PDF (Figure 7) show that in the analyzed month, the system produces either very small amounts of energy of the order of 10–50 kWh, or slightly larger amounts of 100–120 kWh. This is clearly visible in the bimodal nature of the PDF (Figure 7). There are two local maxima for energies of approximately 30 kWh and approximately 120 kWh. This means that we are either unable to charge any electric vehicle with the energy produced or we are able to meet the scenario of daily production of 100 kWh with a probability of 0.3226.

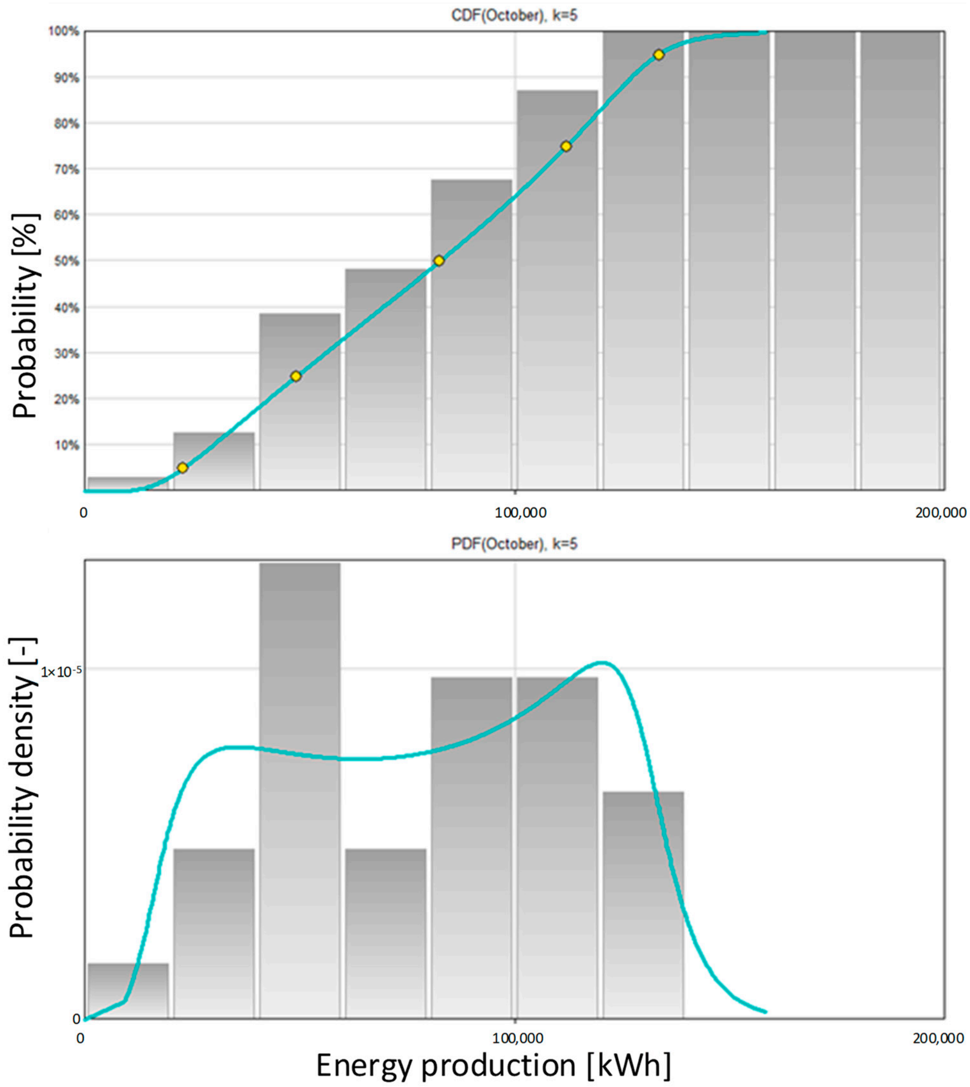

Figure 7. Cumulative distribution function (CDF) and probability density function (PDF) for energy produced by a 50 kWp photovoltaic installation in October 2023.

5. Discussion

Using the strategic model for charging electric vehicles from renewable energy sources described in the previous sections, graphs of the probability of generating a daily amount of energy of more than 100 and 200 kWh in the individual months of 2023 were calculated and are presented in Figure 8. From the calculated probability values, it can be concluded that in Polish geographical climatic conditions, significant amounts of electricity can be generated from a photovoltaic system with a peak power of 50 kWp. The input data for creating the strategic model comes from a specific photovoltaic system installed on the roof of an institutional building in the city of Lublin, Poland. Thus, the model includes geographic context. The strategic model also includes the engineering context related to the type, azimuth, and inclination angle of the installed photovoltaic panels. In this complex context, a photovoltaic system is able to generate an amount of energy greater than 100 kWh every day between March and September with a high probability of over 0.7. In the months from May to September, it is able to generate amounts of energy greater than 200 kWh but with a probability of over 0.5. In the following months, from November to January, the system is unable to generate a daily amount of energy produced greater than 100 kWh. In the autumn and winter months, the amounts of energy produced daily are too small to charge the batteries of the vehicle fleet. Based on the strategic model in question, the vehicle fleet charging manager is able to calculate the probability of the photovoltaic system producing specific amounts of electricity and initially determine the share of green energy in the total energy mix needed to charge the vehicle fleet.

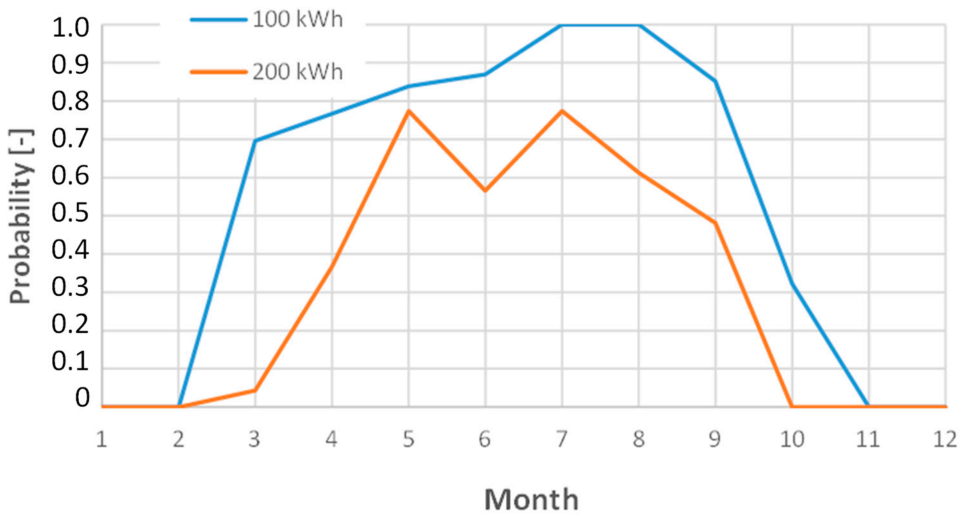

Figure 8. Graphs of the probability of generating a daily amount of energy of more than 100 and 200 kWh in individual months of 2023.

The accuracy of the mathematical model in the strategic model for charging electric vehicles from RES increases with the amount of data entered. Energy production data from several years of operation of the PV system increases the accuracy of the probability calculation. Due to the high quality of the produced PV panels and the very small annual degradation of their performance, it can be assumed that the presented model can be used throughout the life of the PV system. Of course, it is not necessary to introduce a strategic element related to the degradation of the photovoltaic system's performance into the model. It will be reflected in the data regarding the amount of energy produced in the subsequent years of the system's operation. The strategic model based on actual measurement data from PV systems allows us not only to estimate with accuracy the probability distribution of the amount of energy produced by the photovoltaic system per day; it can also be used to detect weather anomalies and diagnose the correct operation of the entire PV system. What is important in the area of the latest market trends it that the approach presented by the authors can be used in a fully automatic way in a system for managing the energy produced from RES, both for charging vehicles and for simply supplying a residential or institutional building with electricity. Due to the use of Bayesian networks to operate the GeNIe 4.1 Academic program, it fits into the trend of using artificial intelligence methods (AI) to support business decisions (business intelligence).

6. Conclusions

Based on their own experience with charging electric vehicles from renewable energy sources, the authors developed a strategic model for charging electric vehicles from renewable energy sources. Due to the origin of the data for analysis, the model takes into account the geographical and climatic context related to the location of the photovoltaic system itself, as well as the engineering context related to the type, azimuth, and inclination angle of the installed photovoltaic panels. The model uses the Metalog probability distribution family to calculate the probability that a 50 kWp peak photovoltaic system will produce a given amount of electricity per day. This energy can be used to charge the traction batteries of a fleet of electric vehicles. Based on calculations from the strategic model, we can conclude that the tested photovoltaic system is able to generate more than 100 kWh of energy every day in the months from March to September with a high probability of over 0.7. In the months from May to September, it is able to generate amounts of energy greater than 200 kWh but with a probability of over 0.5. In the following months, from November to January, the system is unable to generate a daily amount of energy produced greater than 100 kWh. In the autumn and winter months, the amounts of energy produced daily are too small to charge the batteries of the vehicle fleet. The presented strategic model may have practical application in systems for managing electricity produced from renewable energy sources. Based on the strategic model in question, the manager of the charging of the electric vehicle fleet is able to calculate the probability of the photovoltaic system producing specific amounts of electricity and initially determine the share of green energy in the total energy mix needed to charge the vehicle fleet. The strategic model of charging electric vehicles from renewable energy sources is part of the trend of using AI methods to support business decisions (business intelligence).

The authors specifically selected a photovoltaic system with a peak power of 50 kWp in order to easily scale the system to several MWp. The authors intend to continue the research they have started to complicate the model and increase its accuracy. They also plan to include the use of a stationary energy storage facility in the future model, which will allow for an increase in the self-consumption rate of energy produced from renewable energy sources.

Author Contributions: Conceptualization, J.C. and A.M.; methodology, A.M.; software, A.M.; validation, J.C., A.M. and B.Š.; formal analysis, B.Š.; investigation, A.M.; resources, J.C. and A.M.; data curation, A.M.; writing—original draft preparation, J.C., A.M. and B.Š.; writing—review and editing, J.C., A.M. and B.Š.; visualization, A.M.; supervision, J.C.; project administration, B.Š.; funding acquisition, J.C. and A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

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

Abbreviations

AC	alternating current
CCS	combined charging system
CDF	cumulative distribution function
DC	direct current
LFP	lithium iron phosphate (LiFePO4)
LTO	lithium-titanium-oxide
NMC	nickel manganese cobalt
PDF	probability density function
PV	photovoltaic
RES	renewable energy sources
SoC	state of charge
TCO	total cost of ownership

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