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A Statistical Analysis of Long-Term Grid-Connected PV System Operation in Niš (Serbia) under Temperate Continental Climatic Conditions

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Abstract: This study analyzes the grid-connected PV system performances over a 10-year period under temperate continental conditions in Niš. Based on the experimental results, we found the following: the 10-year yearly average values of PV system efficiency, Yf, CF, and PR are 10.49%, 1178.51 kWh/kWp, 13.45%, and 0.87, respectively. The yearly average value of PV performances for a 10-year measurement indicates that the behavior of the given PV system over 10 years does not change significantly. Besides, a mathematical prediction model was obtained through regression analysis, and ANOVA was applied for testing the model's validity. It is shown that the obtained model is statistically significant and enables prediction better than a simple average, the mean values of PV electricity are not changed statistically significantly over the 10 observed years, and there is a statistically significant difference in POA mean radiation during the months over 10 years. Based on the obtained model and POA radiation values, a prediction of the PV system output can be made for similar PV installations. The analysis presented in this study significantly impacts energy prediction, PV energy modeling, and the economics and profitability of the grid-connected PV system utilization, as well as the PV systems' operation planning and maintenance.

Keywords: PV system; POA radiation; efficiency; performance ratio; statistical analysis; ANOVA; post hoc Tukey test

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1. Introduction

Energy shortage is a growing problem today. Climate changes have already been observed, on the one hand, while the use of fossil fuels is becoming more and more limited due to the high energy consumption and Earth's increasing population. Global fossil fuel resources are not yet exhausted; however, their use's negative environmental and social impacts are apparent [1].

The Sun is the largest energy source that has powered and sustained life on Earth for more than 4.5 billion years. Solar energy is more than enough to meet all energy needs worldwide. It is assessed that over one year, the solar energy that arrives at the Earth's surface is 10,000 times greater than the energy necessary for the entire population's needs worldwide. On the other hand, solar energy is an ecologically clean energy whose energy technologies do not pollute the environment. Besides, it represents an energy resource available to every country without import dependence. Photovoltaic (PV) technology is one of the best ways to utilize solar energy and represents one of the most competitive renewable sources for electricity production. The use of PV systems is recently on the rise in many countries, and PV systems are beginning to occupy a significant place in energetics worldwide. Recently, many studies have been conducted on the techno-economic effectiveness of PV systems applications and their benefits in different climatic conditions. These studies are carried out in different countries worldwide, where the climatic specificities of these countries are taken into account. On the other hand, over the last decades, many life cycle assessments (LCAs) of PV systems have been carried out. LCA is an important tool to provide a comprehensive analysis of PV systems compared to conventional energy systems, especially with regard to the greenhouse gas (GHG) emissions assessment [1–7].

In practice, deploying PV technologies is the comprehension of the performance exhibited by each of them once installed outdoors and functions in real climatic conditions. Such investigations are necessary because the outdoor PV electrical characteristics differ from the reference STC characteristics in manufacturer data sheets [8].

Many studies provide PV systems' performance analysis in different periods and locations worldwide. Such studies provide experimental data on the PV systems' operation in real conditions, which are necessary for developing PV software and PV energy modeling and predicting PV system operations, as can be seen in [3,4,9–11]. Considering that many PV systems have been installed worldwide, there are numerous analyses about the performances of installed PV systems under different climatic conditions. On the other hand, some of them provide a comparison of experimental and simulated results of PV system performance parameters. The comprehensive review of the analysis of performance ratio (PR) and final yield (Yf) for 3326 PV systems in Slovenia and a comparison with other countries' PV systems installed is given in. [12]. A comparative performance analysis of two grid-connected PV systems with p-Si and CIS solar cells and power of 1 kWp and 1.36 kWp, respectively, in Southern India is presented in [13], while the prediction of performances, energy losses, and degradation of a 200 kWp grid-integrated PV system using the PVsyst simulation tool in Northern India is given in [14]. An analysis of the long-term performance of 594 PV systems from the power of less than 1 kW to the power of more than 2 MW from different countries (Australia, Germany, Italy, USA, The Netherlands, France, and Belgium) id provided in [15]. This study includes datasets of final yield, PR, and degradation rate of PV systems with different PV technologies, operation years, and installation types. The parameters of reference, array and final yields, system losses, PV and inverter efficiencies, and PR of a 13 kWp grid-connected PV system in Northern Ireland are analyzed on the hourly, daily, and monthly levels over three years of its operations, as can be seen in [16], and the results were compared with the simulation results obtained by TRNSYS simulation tool [17]. Experimental results and simulation results obtained by SAM and PVSyst simulation tools of PR, efficiency, and losses of a grid-connected 960 kW PV system in Italy are analyzed in [18]. Reference [19] provides the results of efficiencies, PR, and degradation rates by testing three PV systems with different PV technologies (c-Si, a-Si, and CdTe) under the same climatic conditions in Ankara (Anatolia) after 4 operation years. A comparison of the experimental and simulated performance of a grid-connected 49.92 kW PV system in the Irish climate over one year is presented in [20]. The energy efficiency analysis, specifically in terms of specific yield, of eight grid-connected and one hybrid PV system with various system configurations, tilt angles, and orientations, installed in southeastern Poland, is presented in [21]. A comprehensive review of PV system performances with a focus on comparative performance studies of different PV systems worldwide is analyzed in [22]. The outdoor performances (PR, system efficiency, and capacity utilization factor) of three grid-connected photovoltaic (PV) systems with c-Si, p-Si, and a-Si PV technologies and total installed power of 5.94 kWp in Morocco are analyzed in [23]. The analysis of PV-generated power in dependence on insolation, ambient, and module temperatures of PV systems with different PV technologies (c-Si, p-Si, and CIGS) in Poland is given in [24].An experimental efficiency analysis of three PV systems with different PV technologies (p-Si, CdTe, and CIGS) under a temperate climate in Poland is given in [25].The performance parameters of a 1.75 kW grid-connected PV system over the four years of its operation in Sydney (Australia) are determined and compared with simulation results obtained by PVSyst. This analysis is given in [26], while the performance indicators, such as performance index, solar fraction etc., are analyzed in [27]. The performance and I-U parameters of two 20-year-old PV systems installed on the west and east side of the building at NREL (USA) are statistically analyzed in [28]. Special attention is focused on the degradation rate, which was found to be 0.8%/year, which is consistent with historical averages. The degradation rate of PV systems with different powers and PV technology and under different climate conditions is also analyzed in [29–37]. All those studies provide helpful insight into energy prediction, the economics and profitability of PV system utilization, and PV systems' operation planning and maintenance. However, there are not many experimental studies on long-term PV system operation in Serbia and surrounding countries with similar climates.

This study provides the original experimental results of PV system performances in Niš (Serbia) for 10 years of its operations. The collected results are statistically analyzed in order to obtain the PV system performances under real operating conditions for a specific region. Based on experimental measurements, the PV system performance parameters over the 10 years of its operations were determined, and a mathematical prediction model was created. Compared with other similar studies, the difference and originality of this study are reflected in terms of 10-year results obtained for a specific location as well as the application of statistical methods for the analysis of a large number of data obtained by experimental measurements of POA radiation and PV electricity. A regression analysis was performed to obtain a prediction model, and an Analysis of Variance (ANOVA) was applied for testing the model's validity. Considering that the variable "years" is a categorical variable and "PV electricity" and "POA radiation" are numerical ones, a one-way analysis was performed. In this regard, the conditions for applying ANOVA were tested, and the O'Brien test was used to check the equality of variances. Thus, the originality of this study compared to similar ones is particularly reflected in the statistical analysis of the results (PV electricity and POA radiation) and the determination of statistical significance in the prediction model. Related to this, this study aims to apply the obtained results in integrating PV systems into the country's electro-power system to increase commercial PV systems applications in Serbia. Besides, this study provides data necessary for increasing the PV modeling accuracy by analyzing the accurate data. On the other hand, the obtained data are useful as guidelines for predicting, planning, and applying PV systems in other locations with similar climates. Besides, the study findings are also useful for degradations analysis of long-term PV system operations, especially in moderate continental climate regions.

Background

The main meteorological parameter that impacts the PV system operation is solar irradiation. It is generally known that the PV module operating voltage is logarithmic-dependent while the current has linear dependence. The main problem is the assessment of solar irradiation effects, which stems from solar irradiation being related to other factors affecting PV performance, such as the clear sky or diffuse radiation due to cloudy sky, low radiation in the early morning or late afternoon (high AM), angle-of-incidence (AOI) radiation effects, spectral response, etc. On the other hand, global solar irradiation is generally measured on a horizontal surface, while the maximum amount of incident solar irradiation is measured on an inclined surface (POA radiation) [10]. Recently, many analytical models have been proposed to estimate the amount of solar irradiation on horizontal (GHI) and inclined surfaces (POA irradiation). These models have different ranges and applicability to specific surfaces and locations. To find the most suitable solar model for a given location, the hourly results predicted by the available models are usually compared with the experimental measurements for the given locations [10,37,38].

In general cases, solar irradiation is usually measured as long-term data on the horizontal surface worldwide, and based on these measurements, solar databases are created. These solar databases, containing solar resource data obtained from the ground and/or derived from satellite imagery, are widely available as open-source or paid datasets. Based on these solar datasets and analytical models for the estimates of solar irradiation on the inclined surface, new bases are formed. The availability of solar databases containing POA irradiation data is limited and very low [10].

In accordance with the reasons mentioned above, the special importance of this study is that it contains long-term measurements of POA solar irradiation and electrical parameters of a grid-connected PV system and provides a statistical analysis of the long-term PV system operation in real conditions.

2. Materials and Methods

For the performance analysis of PV system operation in the real climatic condition in Niš (Latitude: 43°19′28.99″ N, Longitude: 21°54′11.99″ E), 10 monocrystalline silicon solar modules (SST-200WM, Shenzhen Sunco Solar Technology Co., Shenzhen, China), with individual power of 200 W, were mounted right next to each other (in order to minimize cable losses) on the roof of Faculty of Sciences and Mathematics and serially interconnected in a string. The solar modules were set up on the fixed metal construction tilted at an optimal angle of 32° toward the south (Figure 1). The total PV array (solar modules surface) was 16.59 m^2 (or 1.659 m^2/module). The minimum distance between the solar modules and the roof surface was 50 cm to ensure natural air circulation, i.e., a passive air-cooling method for the solar modules was used so that the system balance could take place naturally without any additional (mechanical) technique, as can be seen in Figure 1. It should also be noted that the solar modules were free from any shading.

Figure 1. PV array installed on the roof of the faculty [39].

By appropriate cables (conductors), the solar modules were connected to a DC junction box (DC-RO), then a 2 kW inverter (SunnyBoy 2000HF-30, SMASolar Technology AG, Niestetal, Germany), then to an AC junction box (AC-RO), and finally to a city power grid. The used inverter was a single-phase inverter with a high-frequency (HF) transformer power of 2000 W and an efficiency of 96.3%, providing a single-phase AC voltage of 230 V, 50 Hz. This PV system was connected to the city power grid. However, its effects on the city grid, including the variation of power factor effect of load, PV penetration variation, anti-islanding effect, and introduction of harmonic into the system by the inverter, have not been investigated or considered. It should be noted that over the 10-year period of the PV system operation, there were no problems during the PV electricity transmission to the city network grid.

Global solar radiation on the surface of PV modules (POA radiation) was measured by a sensor unit (Sunny SensorBox), which was also placed next to solar modules at an optimal inclination angle of 32° toward the south. It should be noted that the solar sensor (Sunny

SensorBox) uses an a-Si solar cell and measures POA radiation with a resolution of 1 W/m^2 and measurement accuracy of ±8%. A central communication interface (Sunny WEBBox) was interconnected to the inverter and SensorBox by Bluetooth. The POA radiation data and PV system electrical parameters continuously record every 5 min into the Sunny WEBBox internal memory [10,39]. The SunnyBoy inverter, Sunny WEBBOX, and DC and AC junction boxes were placed indoors in the faculty laboratory, where the optimum room temperature is maintained throughout the year.

A schematic of the grid-connected 2 kW$_p$ PV system in Niš [28] is given in Figure 2.

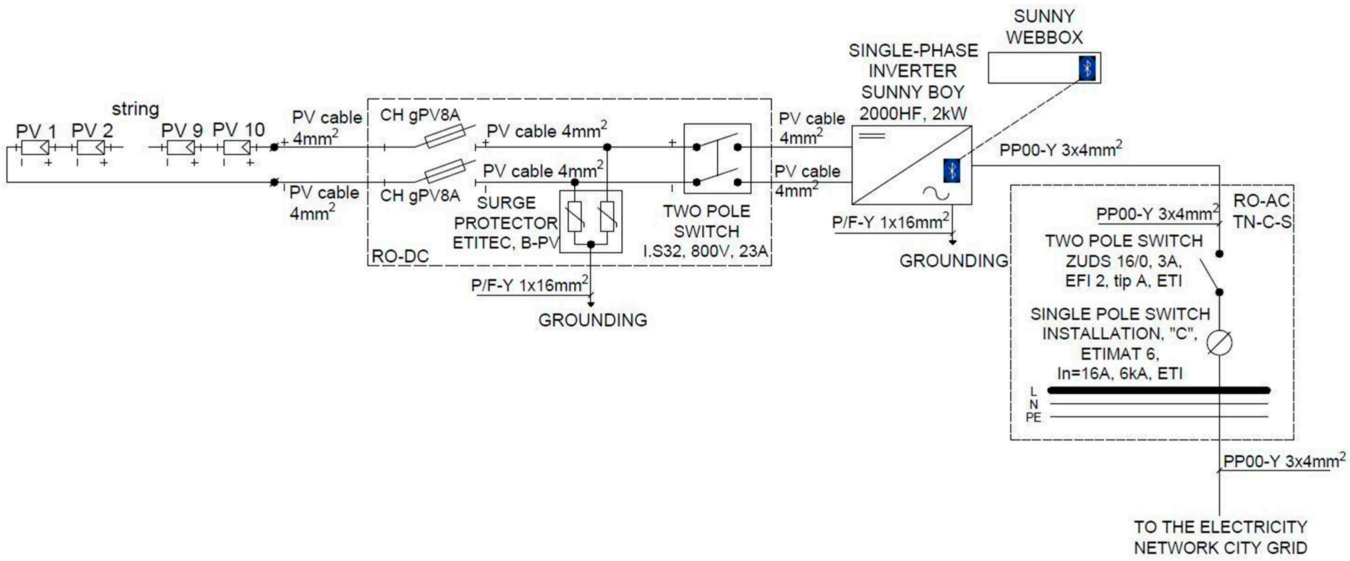

Figure 2. A schematic of grid-connected 2 kW$_p$ PV system [39].

An approximate PV module efficiency at STC can be calculated using the Equation (1) [9]:

$$\eta_{STC} = (I_{SC} \cdot V_{OC} \cdot FF)/I_{STC} \tag{1}$$

where I_{STC} is the reference solar irradiance at STC of 1 kW/m^2, FF is a fill factor of the solar module, I_{SC} is the short-circuit current of solar module, and V_{OC} is the open-circuit voltage of solar module [9]. If it is taken into account that FF = 76%, I_{SC} = 4.64 A, V_{OC} = 57.12 V, and the inverter efficiency η_{inv} = 96.3%, which is based on the specification of the modules and inverter given by the manufactory datasheet and presented in [10], the approximate PV system efficiency at STC (ideally, excluding cable losses) is around 19.4%.

Evaluation of the long-term grid-connected PV system operation in real conditions, based on the statistical processing of experimental data, was performed in two phases:

1. The main performance PV system parameters (PV system efficiency, PR, Y_r, Y_f, and CF), defined by IEC 61724:1998 standard and described in [8,10,39], were determined and are presented in this study.
2. The relationship between two numerical variables (PV system electricity output and total POA irradiation data), obtained by 10-year measurements, was statistically analyzed using JMP Pro software. For that purpose, a regression analysis, analysis of variance (ANOVA), and post hoc Tukey test were applied. ANOVA is a technique for statistical analysis where datasets are compared to provide and determine their significance. ANOVA also describes complex relationships between variables; in this case, they are POA radiation and PV electricity. As results in ANOVA do not identify which specific differences between pairs of means are significant, it is common to use post hoc tests to investigate differences between multiple groups' means. Based on obtained results, the conclusion of the grid-connected PV system application's degradation, efficiency, profitability, and stability during its 10-year operation for a specific climate region was presented.

3. Results and Discussion

As PV manufacturers give the electrical parameters of solar modules, such as open-circuit voltage, short-circuit current, MPP voltage, MPP current, max power, efficiency, and temperature coefficients at STC, and those parameters are not applicable to predict the PV system operation in actual conditions with increased accuracy, it is necessary to determine the main performance parameters of PV system, namely: energy yield (Ey), outdoor efficiency (η), and performance ratio (PR) for a more extended period.

In this section, the experimental results of 2 kWp grid-connected PV system operation in Niš for the period from 1 January 2013 to 31 December 2022 are presented. Since the measurements of all the mentioned parameters were performed every 5 minutes for 10 years, the statistical processing of the data calculated first the hourly, then the daily, and finally the monthly and annual values. Further on, the experimental results will be presented on a monthly level for 10 years.

3.1. Performance Parameters

The 10-year average values of energy yield (Ey) depending on the 10-year average values of total POA radiation reached on the total PV array area by month are given in Figure 3.

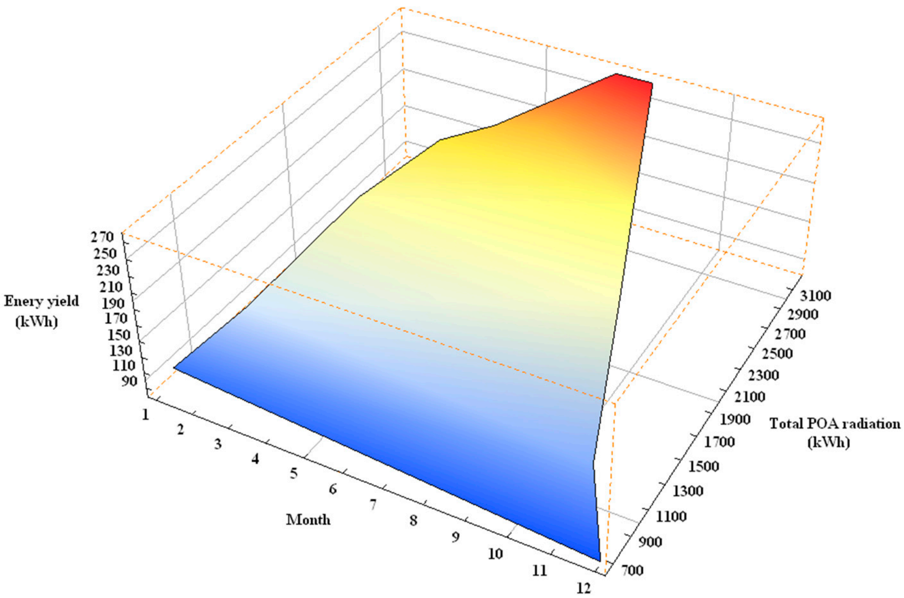

Figure 3. The 10-year average values of energy yield (Ey) depending on the 10-year average values of total POA radiation reached on the total PV array area by month.

The 10-year average values of total POA radiation on the total PV array by month range from 667.158 kWh (December) to 3204.684 kWh (July), while 10-year average values of energy yield by month range from 82.196 kWh (December) to 276.746 kWh (August), as can be seen in Figure 3.

One of the main parameters of PV system performance in real conditions is the efficiency of the given system (η_{syst}), which is determined as the ratio of the PV system output (AC output from the inverter and transmitted to the city grid) to the total POA radiation on the PV array [10,39]. The 10-year average values of PV system energy efficiency (η_{syst}) by month are given in Figure 4.

The 10-year average values of PV system energy efficiency (η_{syst}) by month range from 8.61% (July) to 12.61% (January), while the PV system efficiency at STC is 19%.

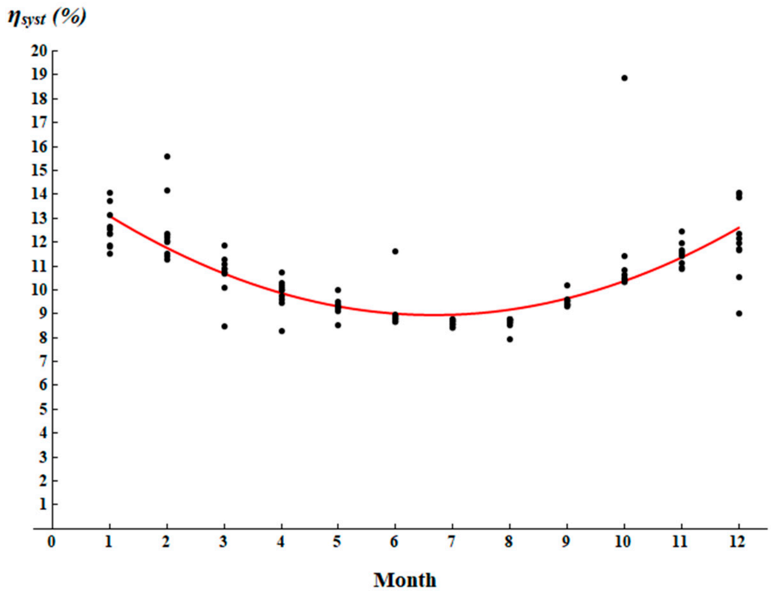

Figure 4. The 10-year average values of PV system energy efficiency (η_{syst}) by month.

The reference yield (Y_r) represents the ratio between the total POA radiation (in kWh/m^2) and the reference solar radiation of 1 kW/m^2 (reference solar radiation is radiation at STC) and is a function of the geographical location and orientation of the PV array. On the other hand, the specific yield factor (Y_f) represents the ratio between the PV system output (in kWh) and the total installed power of the PV system (in kW$_p$). The specific yield factor (or final yield) is usually utilized to normalize the produced system energy relative to the PV system size. It could be said that Y_f is a good parameter for comparing the energy produced by different sized PV systems [10]. The ratio between the specific yield factor (Y_f) and the reference yield (Y_r) for 10-year measurements is given in Figure 5.

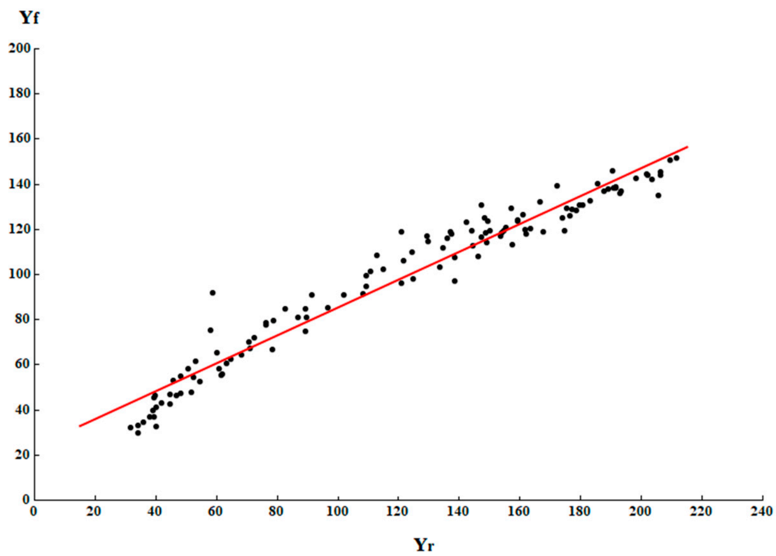

Figure 5. The ratio between the specific yield factor (Y_f) and the reference yield (Y_r) for 10-year measurements.

Figure 5 shows that there is a linear dependence between the specific yield factor and the reference yield. Plotting the regression line for each month during the 10 years (Figure 5) allows for the identification of the slope and, therefore, the average monthly performance ratio. In this case, the regression coefficient (slope in the regression model) amounts to 0.617536 and responds to the average change of the expected value of the dependent variable Y_f for the unit change of the independent variable Y_r. Thus, the ratio between the specific yield factor (Y_f) and the reference yield (Y_r) represents Performance

Ratio (PR). Hence, the PR defines the rate of effective produced energy with the energy the PV system would generate if it continually worked on its efficiency at standard test conditions. So, the PR comprises all PV optical and electric losses in a system without being directly dependent on input parameters such as meteodata (temperature, solar radiation, wind speed, cloudiness, snow, precipitation, presence of aerosols, etc.), module efficiency, and orientation of the PV array [10,29–37].

Graphics of the change of yearly average values of the Performance Ratio (PR) for a 10-year period is given in Figure 6.

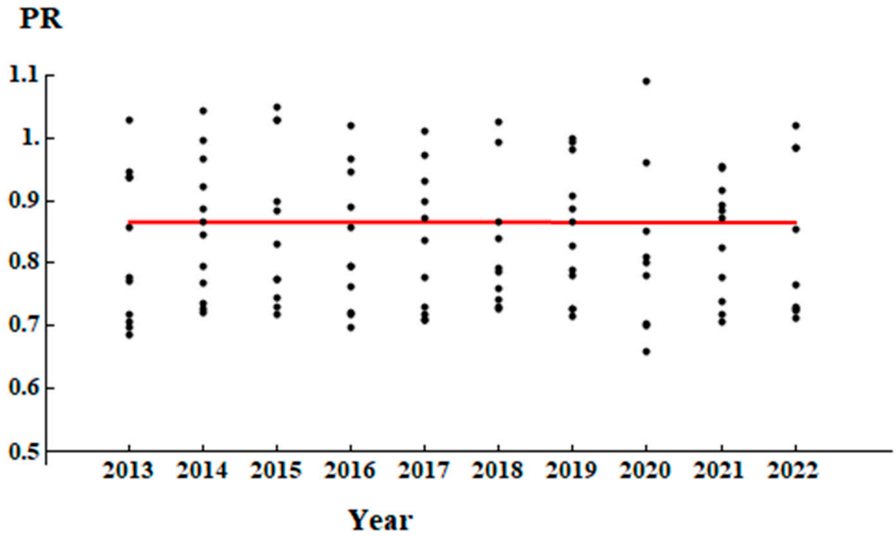

Figure 6. Graphics of the change of yearly average values of Performance Ratio (PR) for a 10-year period.

The yearly average values of PR for the 10 years, from 2013 to 2022, range from 0.849 to 0.93. On the other hand, the 10-year average values of PR by month range from 1.01 (December) to 0.713 (July). A PR higher than 1 is uncommon and can only be accomplished under particularly favorable weather conditions, such as high solar insolation values when cell temperatures are much below the temperatures at STC. In this case, deviations of PR values from the usual ones occurred in the winter months (December, January, and February) due to higher insolation, mild temperatures, and less precipitation and snow, which is unusual for that time of year. On the other hand, plotting the regression line of PR during the 10 years shows a very slight linear decrease over the years, with a regression coefficient of |−0.0000583|, representing the slope in a regression model. So, in this case, the PR, that is, the rate of effective produced energy with the energy the PV system would generate if it continually worked on its efficiency at STC, did not change statistically significantly over the 10 years of its operation. In other words, the losses in the PV system, which include soiling and aging of the system components, during its 10-year operation are insignificant (almost negligible) for the observed period. Thus, as PR is a quantitative characteristic of all PV system losses, including soiling and aging of the system's components, the results show that the behavior of the given PV system over 10 years of its operation does not change significantly; that is, the PV system degradation over 10 years is minimal. Based on the specific yield factor, the capacity factor (CF) can be calculated, which presents the ratio of the yearly specific yield factor and yearly theoretical PV production capability. In this case, the yearly average of CF over the 10-year period range from 12.88% (2014) to 14.02% (2019).

On the other hand, the average value of total energy losses in the given PV system could be calculated as the difference between Y_r and Y_f, and for the 10-year measurement period, it is 22.3%.

Although solar radiation, to a great extent, affects the PV arrays' electricity output, ambient temperature also affects electricity production and, therefore, other PV system performance parameters, such as PR. Ambient temperature can lead to heating of the solar module surface, resulting in reduced PV system efficiency. Generally, an increase in temperature of 1 °C causes a decrease in relative PV efficiency between 0.14% and 0.47%, depending on the PV installation type [40]. Recently studies have shown that there are different PV cooling methods that noticeably increase the PV system efficiency but passive ventilation of the PV system, i.e., PV cooling under natural air convection, is the simplest and most inexpensive method for application [40,41]. With the natural air convection appearing behind the PV modules, the temperature of solar cells can decrease by about 15–20 K, as reported in [42]. In this case, as the ventilation of a given PV system unfolds naturally (passive air cooling), so solar modules' cooling is done only by the wind influence. The ratio between the average monthly values of PV system energy efficiency (η_{syst}) and the wind speed (v) for 10-year measurements is given in Figure 7.

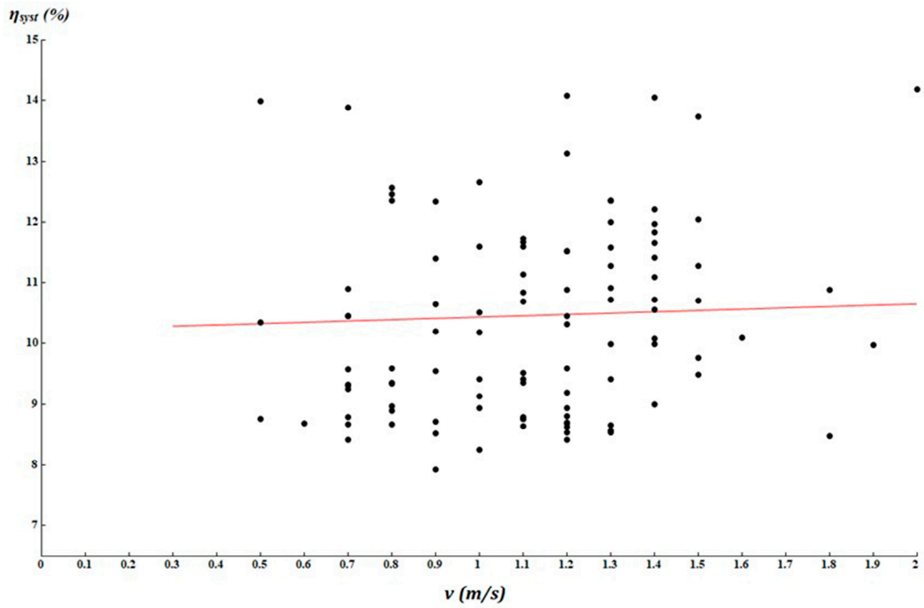

Figure 7. The ratio between the average monthly values of PV system energy efficiency (η_{syst}) and the wind speed (v) for 10-year measurements.

Based on simple linear regression, the plotted regression line for each month during the 10 years (Figure 7) allows for the identification of the slope so that, in this case, the regression coefficient (slope in the regression model) amounts to 0.214411 and responds to the average change of the expected value of the dependent variable η_{syst} for the unit change of the independent variable v. Figure 7 also shows that, with increasing wind speed, PV system efficiency linearly increases. However, this type of PV cooling does not significantly increase the system efficiency. It should be noted that wind speed values for Niš were taken from the website of the Hydrometeorological Institute of the Republic of Serbia (https://www.hidmet.gov.rs/ciril/meteorologija/klimatologija_godisnjaci.php, accessed on 8 May 2023.). It was also observed that the ratio between the average monthly values of PR and the wind speed (v) follows the same trend over the 10-year measurements, as is the case with PV system efficiency.

Performance comparison of grid-connected PV systems with similar installation, power (1–3 kW), and PV technology in the different climatic zone is given in Table 1 [13,22].

As the chosen PV systems, shown in Table 1, and PV system in Niš have similar power and PV configurations, it can be concluded that PV system efficiency and PR are lower in countries with a subtropical climate due to the negative impact of higher ambient temperatures and, therefore, higher solar module temperatures. PV systems with other PV technology and higher powers, installed worldwide and shown in [12–27,32], are not comparable to a given PV system in Niš.

Table 1. Performance comparison of grid-connected PV systems power of 1–3 kW with similar installation and crystalline-Si technology in different climatic zone [13,22].

Location	Power (kW)	PV Technology	Final Yield (h/d)	System Efficiency (%)	PR (%)	CF (%)	Climate	Year/Duration (Years)
Serbia—current study	2	c-Si	3.23	10.49	87	13.45	Temperate/continental	2022/10
Ireland	1.72	c-Si	2.4	12.6	81.5	10.1	Temperate/oceanic	/
Norway	2.1	p-Si	2.55	13–14	83.06	10.58	Temperate/subarctic	/
Brazil	2.2	p-Si	4.6	13.3	82.9	19.2	Tropical/subtropical	/
China	3	p-Si	2.86	10.73	80.6	/	Humid subtropical	2009/3
Morocco	2.4	c-Si, p-Si	4.34	11.67	76.7	18.16	Hot semi-arid subtropical	2018/4
Morocco	2.04	c-Si	4.34	11.7	76.7	/	Hot semi-arid subtropical	2015/2
India	2	p-Si	/	/	70	/	tropical	2019/1
Spain	2	/		7.11	64.5		Subtropical/Mediterranean	1997/1
Turkey	2.35	c-Si, p-Si	/	13.26	91	/	Humid subtropical	2014/1
Oman	1.4	p-Si	/	/	84.6	21	Hot desert	/
Korea	3	c-Si	/	7.9	63.3	11.5	Humid subtropical	2003/1

3.2. Statistical Analysis of PV System Electricity and Total POA Radiation Data during 10 Years of Measurements

For statistical analysis of the results, the JMP Pro software is used [43]. The regression analysis is used for building a mathematical model for the prediction of PV electricity at a given POA radiation on a PV array. The model enables a specific value of POA radiation (independent variable) to calculate PV electricity (dependent variable) simply. The criterion for estimating the regression coefficients is a least square method. In order to assess the adequacy of a linear regression model, the statistical hypotheses about the model parameters are tested by *T*-test. To test hypotheses about the slope and intercept of the regression model, the error component in the model has to be normally distributed and also independently distributed. The significance of the regression is tested via Analysis of Variance (ANOVA). The existing significance shows that the model gives more information about the system than the simple average. The one-way ANOVA is also used for comparing the groups of data (groups is a categorical variables). The significance of the ANOVA shows that at least two groups have different means. ANOVA also uses to describe complex relationships between variables, as can be seen in the [36,43–47]. As results in ANOVA do not identify which specific differences between pairs of means are significant, it is common to use post hoc tests to investigate differences between multiple groups' means while controlling for experimental error [47].

The PV and POA radiation are numerical variables. The relationship between numerical variables can be graphically shown via a scatter plot (Figure 8). A numerical representation that shows the strength of the relationship between numerical variables is the correlation coefficient. The resulting value of the correlation coefficient between two numerical variables, PV electricity and POA radiation on the PV array, is 0.90059, which shows that the relationship between these two variables is highly positive. The strong and positive relationship tendency between the two variables can also be seen in Figure 8. Such a high value of the correlation coefficient enables the formation of a regression model between the variables.

A linear regression model, developed by the least squares method with R square and R square adjusted at 0.811062 and 0.809344, respectively. The obtained model Equation (2) is:

$$y = 58.326117 + 0.0685116{*}x, \quad (2)$$

where y is PV electricity in kWh, while x is the total POA radiation on PV array in kWh. This model, based on data obtained over 10 years of investigation, can be used for prediction PV electricity value for the known POA radiation value.

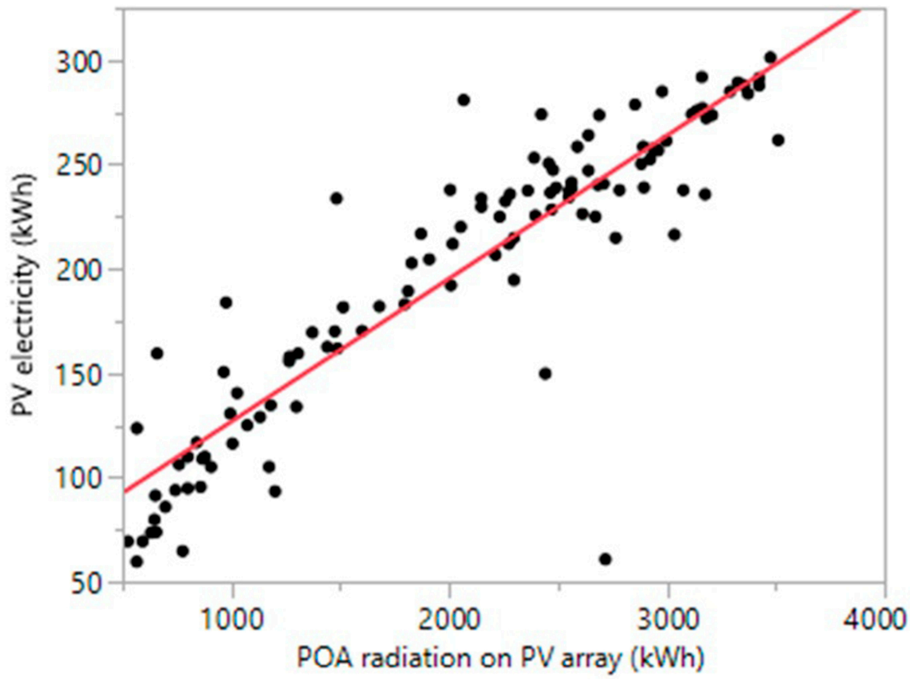

Figure 8. Scatter plot of two numerical variables, PV electricity and POA radiation on PV array with fitted line—red line.

In order to test validity of the model, an ANOVA was conducted. The analysis of variance of the regression model is given in Table 2, while the parameter estimates are given in Table 3.

Table 2. Analysis of variance of the regression model.

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	421,038.40	421,038	472.2001
Error	110	98,081.77	892	Prob> F
C. Total	111	519,120.17		<0.0001

Table 3. Parameter estimates.

Term	Estimate	Std Error	t Ratio	Prob > |t|
Intercept	58.326117	7.002889	8.33	<0.0001
POA radiation on PV array (kWh)	0.0685116	0.003153	21.73	<0.0001

The ANOVA showed that the model is statistically significant $\alpha = 0.05$ with a *p*-value less than 0.001, which means that the model provides significantly more information than the simple average. The T test was used to test the significance of the intercept and x variable, and both are statistically significant with the *p* value less than 0.001.

Figure 9 considers POA radiation on PV array during the months measured over 10 years.

In Figure 9, the black line is the mean of the data. The top and bottom of green diamonds represent the confidence interval for each year. The middle line across the diamond represents the mean of the POA radiation for each group (month). The circles represent the results of Tukey–Kramer test, and circles with the same color are statistically significantly different.

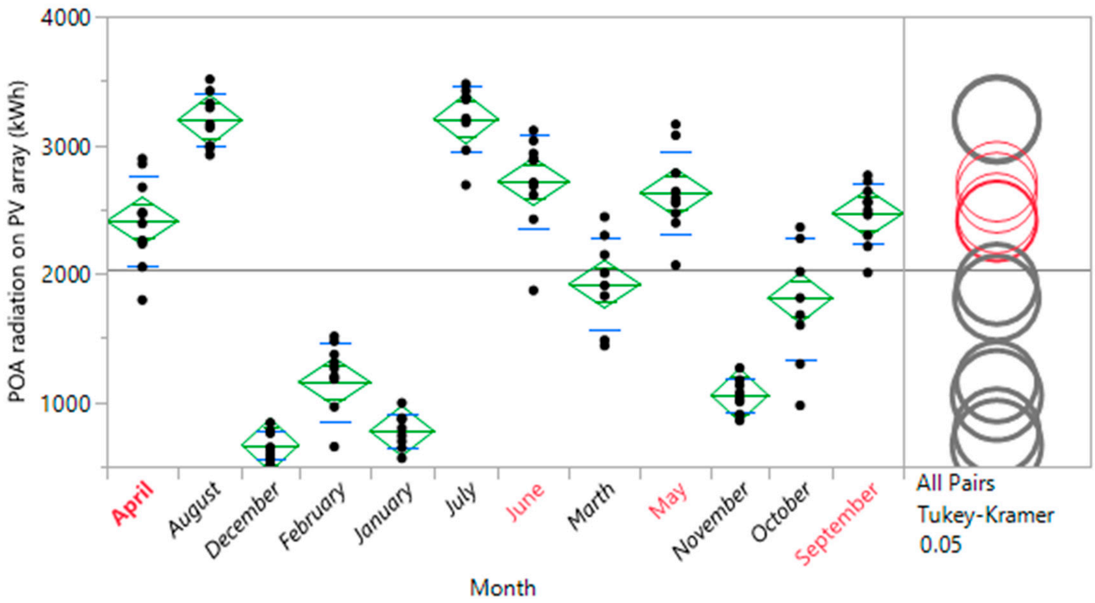

Figure 9. POA radiation on PV array during the months measured over the 10-year period.

The O'Brien test for checking equality of variances, with a *p*-value of 0.0692, shows that based on the data, there is no evidence that shows statistically unequal variances between the groups.

Results of the ANOVA, which are related to an analysis of variance of POA radiation on PV array by "months" groups, are shown in Table 4, and a *p* value less than 0.001 shows that at least the mean between two groups of data is statistically significantly different. However, with ANOVA it is not clear which of them are significantly different. For that reason, the post hoc Tukey test is performed (Table 5).

Table 4. Analysis of variance of POA radiation on PV array by "months" groups.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Month	11	81,047,311	7,367,937	85.1508	<0.0001
Error	100	8,652,807	86,528		
C. Total	111	89,700,118			

Table 5. The results of the Tukey test—connecting letters report.

Level						Mean
July	A					3204.6841
August	A					3194.4330
June		B				2715.8129
May		B				2629.4805
September		B				2470.4103
April		B				2409.3351
Marth			C			1918.8154
October			C			1810.7883
February				D		1158.8864
November				D	E	1054.8455
January				D	E	776.5689
December					E	667.1575

As was expected, the mean of POA radiation has the highest values on July and August. Within the Table 5, the months which are not statistically significantly different are marked with the same letter, while those that are statistically significantly different have letters that are also different.

It should be noted that levels not connected by the same letter are significantly different.

The values of PV electricity during the 10-year period are also analyzed and presented in Figure 10.

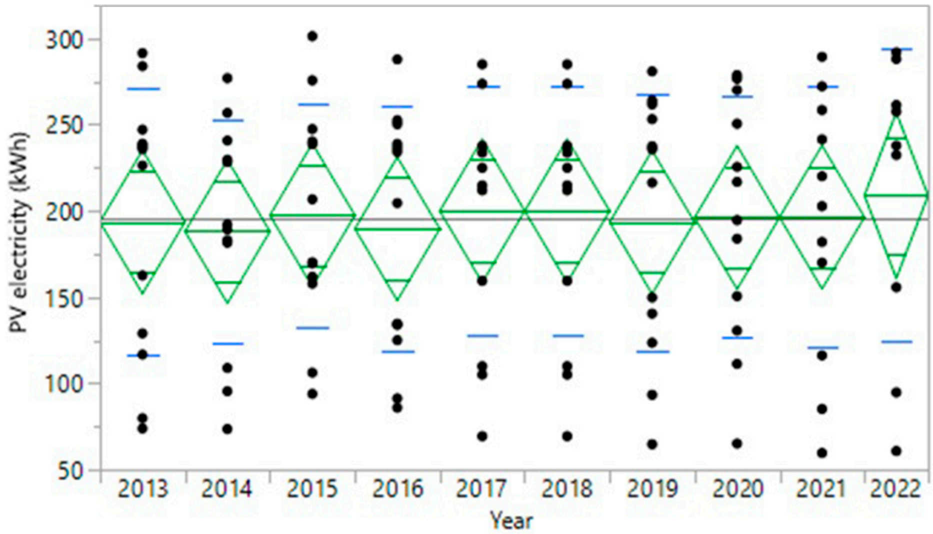

Figure 10. PV electricity during the 10-year period.

In Figure 10, the black line is the mean of the data. The top and bottom of the green diamonds represent the confidence interval (1-alpha) ×100 for each year (group). The middle line across the diamond represents the mean of the group (mean of the PV electricity within the specific year). The height of the diamonds is proportional to the reciprocal of the square root of the number of observations in the groups. The horizontal extent of each group along the horizontal axis is proportional to the sample size for each level of year variable. It means the narrower diamonds are usually taller. The mean line across the middle of each diamond represents the group mean (mean of PV electricity of the year).

Considering that the variable "years" is a categorical variable and "PV electricity" is numerical one, a one-way analysis needs to be performed. In this regard, it is necessary to test the conditions for applying ANOVA. The O'Brien test is used to check the equality of variances.

The obtained *p*-value of 0.9860 in the O'Brien test indicates that it cannot be said that the variance along the groups (the group is the PV electricity values for a specific year and it means that the sample consists of 10 groups/years) is not equal and ANOVA can be used. The analysis of variance of the PV electricity by years (groups) is given in Table 6.

Table 6. Analysis of variance of the PV electricity by "years"—groups.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Year	9	3305.57	367.29	0.0696	0.9999
Error	107	564,654.35	5277.14		
C. Total	116	567,959.92			

The ANOVA shows, with a *p*-value of 0.9999, that it cannot be stated that the mean values of PV electricity between the groups differ from each other. In other words, based on the data obtained over 10 years, it cannot be stated that the mean values of PV electricity change statistically significantly with the years. Because POA radiation and PV electricity are statistically speaking matched pairs data, it means that the same conclusion related to PV electricity could be applied on POA radiation in terms of mean difference over the 10 years.

Thus, the mathematical prediction model was obtained by regression analysis, and the model's validity was tested by ANOVA. As the obtained model is statistically significant and allows for a better prediction than the usual average, the mean values of PV electricity were found to not change statistically significantly during the 10 observed years, while there was a statistically significant difference in the mean POA radiation during the months over 10 years; by applying the obtained model, the PV system output for similar PV installations can be predicted with significant accuracy.

4. Conclusions

This study analyzes the performance and reliability parameters of a long-term grid-connected PV system operation that was exposed to moderately continental climatic conditions in Niš (Serbia).

Based on the experimental results, this study shows that:

- The yearly average values of POA radiation on a south-oriented and optimally inclined plane and total POA radiation on the PV array for a 10-year measurements level are 120.5931 kWh/m^2 and 1,999,512 kWh, respectively.
- The total electricity production of the PV system for 10 years of its operations is 22,934.65 kWh.
- The yearly average value of PV system efficiency, for the 10-year measurements level, is 10.49%, which is almost two times less than the given efficiency at STC, and the relative error of yearly average values of PV system efficiency, observed from year to year, range from 0.34% to 6.16%.
- The yearly average value of specific yield factor (Y_f) for the 10-year measurements level is 1178.51 kWh/kW$_p$.
- The yearly average value of CF over the 10-year period is 13.45%.
- The yearly average value of PR for the 10-year measurements level is 0.87, and the relative error of yearly average values of PR, observed from year to year, range from 0.97% to 6.83%. On the other hand, the PV system, which uses highly efficient components and is designed appropriately, shows a PR near 90% ("good" performances are >84%). Thus, the experimental results indicate that the behavior of the given PV system over 10 years of operation does not change significantly.

Based on a statistical analysis of PV system electricity and total POA radiation on PV array data over 10 years of measurements, it can be concluded that:

- A high correlation coefficient value allows for the formation of regression model between PV electricity and POA radiation of the PV array. The obtained model is statistically significant and enables prediction better than the simple average.
- ANOVA shows that the mean values of PV electricity are not statistically significant changed over the 10 observed years.
- ANOVA and post hoc Tukey test show that there is a statistically significant difference of POA mean radiation during the months over 10 years and that the highest values of POA radiation are in July and on August. The Tukey test enables the months to be separated within the groups based on difference of POA radiation on PV array. The months within the groups are without statistically significant differences of POA radiation, while the months in various groups differ statistically significantly in terms of POA radiation.
- Based on the POA radiation values and by applying the obtained model, a prediction of the PV system output can be made for similar PV installations.

It should be also noted that, by making the presented results publicly available, this research could benefit researchers in increasing the accuracy of modeling, prediction, and the cost-effectiveness of PV systems over a longer period of their operation.

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