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PROCENA UČINKA SOLARNOG FOTONAPONSKOG SISTEMA UPOTREBOM SOFTVERA ENERGYPLUS I VEB APLIKACIJE PVGIS

Key words:
EnergyPlus; PVGIS; solar PV system; simulation

EVALUATION OF SOLAR PHOTOVOLTAIC SYSTEM PERFORMANCE USING ENERGYPLUS SOFTWARE AND THE PVGIS WEB APPLICATION

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Precizna procena učinka solarnog fotonaponskog (FN) sistema zavisi od preciznosti softverskih alata koji se koriste za simulaciju. U ovom radu izvršeno je poređenje softvera EnergyPlus i veb-aplikacije PVGIS. EnergyPlus predstavlja inženjerski softver koji omogućava detaljno simuliranje rada FN sistema, uzimajući u obzir veliki broj ulaznih parametara koji utiču na njihov učinak. S druge strane, veb-aplikacija PVGIS nudi pojednostavljen pristup, ali njena tačnost u poređenju sa inženjerskim simulacija nije uvek jasno definisana. Cilj ovog rada je da ispita u kojoj meri PVGIS može da pruži rezultate uporedive sa onima dobijenim pomoću EnergyPlus simulacija. U tu svrhu sprovedene su uporedne simulacije za devet različitih lokacija na teritoriji Republike Srbije. U okviru veb-aplikacije PVGIS realizovane su simulacije primenom dve datoteke meteoroloških podataka (SARAH3 i ERA5), koje su potom upoređene sa rezultatima dobijenim korišćenjem EPW datoteke meteoroloških podataka u softveru EnergyPlus. Rezultati ukazuju na razlike u rasponu od 3,23% do 9,11% između SARAH3 i EPW datoteka, kao i od -2,89% do 1,82% za ERA5 i EPW datoteke. Dodatno, sprovedena je analiza za poznatu lokaciju u centru Kragujevca, na kojoj bi se solarni prijemnik tokom većeg dela godine nalazio u senci. Rezultati EnergyPlus simulacije pokazali su 63,4% manju proizvodnju u odnosu na PVGIS simulaciju sa SARAH3 datotekom, odnosno 65,6% manju u poređenju sa ERA5 datotekom. Dobijeni rezultati jasno ukazuju da PVGIS veb-aplikacija može pružiti dovoljno precizne procene rada solarnih FN sistema kada se koristi ERA5 datoteka, samo ako su analizirane lokacije neosenčene.

The accurate assessment of a solar photovoltaic (PV) system depends on reliability of the software tools used for simulation. This study compares software EnergyPlus and PVGIS web application. EnergyPlus is an engineering-oriented software that enables detailed modeling of a PV system performance, considering a large number of input parameters that affect energy yield. The PVGIS web application, on other hand, offers a simplified approach, but its accuracy compared to engineering simulations is not explicitly defined. The aim of this study is to examine to what extent PVGIS can provide results comparable to those obtained using EnergyPlus simulations. For this purpose, comparative simulations were carried out for nine different locations across the Republic of Serbia.

Within the PVGIS web application, simulations were performed using two meteorological datasets (SARAH3 and ERA5), which were then compared with the results obtained using the EPW weather files in EnergyPlus. The results show differences ranging from 3.23% to 9.11% between the SARAH3 and EPW datasets, and from -2.89% to 1.82% between the ERA5 and EPW datasets. Additionally, an analysis was conducted for a known location in the city center of Kragujevac, where the PV modules would remain shaded for most of the year. The EnergyPlus simulation results indicated a 63.4% lower energy yield compared to the PVGIS simulation using the SARAH3 dataset and 65.6% lower compared to the ERA5 dataset. The obtained results clearly indicate that the PVGIS web application can provide sufficiently accurate performance estimations of solar PV systems when the ERA5 dataset is used, only if the analyzed locations are completely unshaded.

1. Introduction

Making the decision to invest in a solar photovoltaic (PV) system is rarely an easy choice, as it requires a level of technical and financial understanding that most customers do not possess. In the early stages of consideration, individuals typically have incomplete information and often encounter negative short-term experiences related to administrative and financial aspects of the investment. Meanwhile, the positive outcomes tend to be delayed and less tangible [1,2]. Providing investors with a reliable software capable of accurately modeling PV system performance can help them estimate the return on investment more precisely, thus enhancing transparency, supporting more informed decision-making and reducing negative perceptions associated with this technology.

To address these challenges, numerous software tools and web applications have been developed for simulating the performance of PV systems. *Kazem et al.* [3] evaluated 36 different software used for PV system design over the past eight decades. *Ashraful Islam et al.* [4] compared five widely used software packages: SAM, PVsyst, HOMER, PV*SOL and RETScreen, highlighting their accuracy. *Wu* [5] compared simulation results of PVWatts and EnergyPlus, finding that with default models and weather datasets, the annual deviation ranged between 4% and 7%, depending on the tilt angle. *Gurupira and Rix* [6] evaluated three commercially available PV system simulation tools PVSyst, SAM and PVLib, by modeling an existing plant in South Africa, and comparing the results to the actual yield. The resulting deviations were 3.37%, 3.86% and 5.07%, respectively. *Mohammadi and Gezegin* [7] conducted a comparison among PVSyst, PVGIS and HOMER software for modeling a 5 MW solar power plant in Afghanistan. The results showed that the highest energy yield was provided by the PVSyst software, while PVGIS and HOMER provided 10.6% and 2% lower yields, respectively. *Psomopoulos et al.* [8] presented comparison of the PVGIS, PVWatts and RETScreen web applications with real measurements of existing PV plant featuring a two-axis tracking mechanism, observing that all three achieved relatively accurate results. Similarly, *Larasati and Tengah* [9] compared three web-based applications (GSA, PVWatts and PVGIS) with experimental data, reporting an average deviation of 14.72% for PVGIS.

In this study, the Photovoltaic Geographical Information System (PVGIS), a widely used web application, developed by the European Commission, was assessed and compared to the EnergyPlus software.

According to [10,11] PVGIS is an accurate and free online tool that provides information on solar radiation and photovoltaic system performance for any location in the world except North and South Poles. The tool takes into account the exact location, orientation, panel tilt and installed power, while using historical data and mathematical models to simulate the solar irradiation received by the solar system.

However, as *Meral and Furkan* [12] point out, solar irradiance is not the only factor influencing the PV system performance. Their study identifies various atmospheric conditions that significantly affect the efficiency of PV panels. Among them, module temperature is recognized as the most influential parameter, as the increase in cell temperature leads to a linear decrease in panel efficiency. PV modules installed on rooftops can reach temperatures of 50-70ºC, considerably reducing their nominal efficiency. In addition to module temperature and irradiance intensity, other atmospheric parameters such as, ambient temperature, wind speed, and shading also play crucial roles. Although this study does not quantify the effect of each factor, it clearly demonstrates that such parameters must be integrated into simulation models to ensure realistic performance estimations.

Das et al. [13] presented a comprehensive overview of photovoltaic power forecasting methods, emphasizing that model accuracy is strongly influenced by both data quality and model complexity, further highlighting the importance of using a detailed meteorological dataset to ensure realistic simulation outcomes. They also report a strong correlation between PV power output and solar irradiance, compared with atmospheric temperature and other meteorological variables, underlining the necessity of accurate solar radiation data for reliable simulations. Regarding this, *Jiménez-Torres et al.* [14] emphasize the importance of adequate meteorological datasets for effective solar energy system modeling. They note that while several datasets provide data on horizontal solar radiation, converting it to tilted-plane irradiance introduces potential errors. To address this challenge, they developed a software tool named OrientSol 3.0, and compared its performance to PVGIS application for two cities in Spain- Madrid and Jaén, resulting in an average PVGIS errors of 3.55% and 3.82%, respectively.

Lastly, among all the input factors affecting PV panel efficiency (except material accumulation on the panel surface) EnergyPlus and PVGIS take into account all of them, though with different precisions. However, an important question arises- whether PVGIS can incorporate the effect of shading in its simulations, and if so, to what extent.

In light of these considerations, it is evident that while web applications such as PVGIS provide valuable and accessible estimations, their simplified approach can limit their precision under real-world conditions. On the other hand, advanced engineering tools such as EnergyPlus enable a more comprehensive and precise estimations of the PV performance. Therefore, the goal of this paper is to demonstrate that accurate PV system modeling requires an adequate engineering approach, one that integrates detailed climatic, technical, and operational parameters to achieve reliable and realistic results.

2. Methodology

The power output of a selected PV panel- LUXEN 585W (technical specifications provided in [15]) was assessed in this study using the PVGIS web application and the EnergyPlus software. The simulations were conducted for nine cities in Serbia: Subotica, Novi Sad, Belgrade, Kragujevac, Zlatibor, Negotin, Niš, Vranje, and Priština. The exact coordinates for the nine locations were extracted from the EnergyPlus WeatherData (EPW) files, representing the meteorological stations used in the simulations, and applied as input coordinates in PVGIS to ensure that both tools modeled the same geographical locations. Within PVGIS, two meteorological datasets were used (PVGIS-SARAH3 and PVGIS-ERA5) to evaluate potential differences in the simulation results. For EnergyPlus, the corresponding EPW weather files were used. Additionally, to determine whether the PVGIS accounts for shading effects, an extra simulation was conducted for the city of Kragujevac. In this case, a PV panel was modeled in EnergyPlus as being shaded by a nearby building located in the city center, while in the PVGIS application the same location was used, representing the location where the PV panel would remain shaded for most of the year. The detailed methodology is described in the following sections.

2.1. PVGIS

PVGIS is a free online tool that enables users to estimate the energy production of a PV system based on several simple input parameters, as shown in Table 1. Users can also select which solar radiation dataset to apply among PVGIS-SARAH3 and PVGIS-ERA5 [16].

The SARAH3 is a satellite-based product developed from Meteosat observations. It uses data from the period 2005-2023, covering the Europe, Central Asia, Africa and parts of South America [17]. For locations not included in the SARAH3 coverage, the ERA5 dataset is advised. ERA5 is a global reanalysis product that also uses data from 2005 to 2023 to generate model estimates of solar and meteorological conditions worldwide [17]. Since these two datasets are produced using different methodologies, the simulation results obtained from them could be different.

The key parameters ensuring accurate PV system performance simulations included within these two datasets are dry bulb temperature, relative humidity, global horizontal irradiance, direct (beam) normal irradiance, diffuse horizontal irradiance, infrared radiation downwards, wind speed, wind direction and air pressure.

Input parameters used in the PVGIS simulations are presented in Table 1. For the purpose of this analysis, the system loss effect was neglected. Regarding the panel slope, the value of 35.5º was adopted, representing the average of the recommended slope values for all the nine locations, determined using the “Optimize slope“ function in the PVGIS.

Table 1. Input parameters used in PVGIS simulations

PV technology	Installed peak PV power [kWp]	System loss [%]	Mounting position	Slope [º]	Azimuth [º]
Crystalline silicon	0.585	0	Free-standing	35.5	0

2.2. EnergyPlus

EnergyPlus is an open source, whole building energy simulation software developed by the U.S. Department of Energy to model the thermal behavior and energy performance of buildings under dynamic climatic and operational conditions. It integrates the calculation of building envelope heat transfer, HVAC operation, renewable energy systems, and control strategies within a single simulation environment [18-20]. EnergyPlus is widely recognized as the most commonly used software tool in the scientific community for predicting building energy performance. It is confirmed and verified [21-25], and provides the ability to simulate the energy behavior of very complex buildings under real weather conditions.

In this study, the PV system performance was simulated in EnergyPlus using the *PhotovoltaicPerformance:EquivalentOne-Diode* model. The input parameters for the PV module were adopted from [15]. This model is based on the single-diode circuit representation of a solar cell and accounts for parameters such as the short circuit current, open circuit voltage, module current and voltage at maximum power, and temperature coefficients, allowing accurate estimations under varying irradiance and temperature conditions [26,27].

The meteorological data were obtained from EPW files for all nine analyzed locations [28]. These datasets are derived from satellite observations and reanalysis datasets based on data from actual meteorological stations, covering the period from 2009 to 2023. Each EPW file provides a set of hourly climatic variables adopted for EnergyPlus. The key parameters ensuring accurate PV system performance simulations included withing EPW files are geographical location of the station, elevation, dry-bulb and dew-point temperature, wind speed and direction, atmospheric pressure, solar irradiance data, albedo, sky clearance and visibility data.

The system was modeled as a fixed, roof mounted PV installation with a slope of 35.5º, and south-facing orientation (Figure 1). Although mounted on the roof the air circulation is allowed on all sides of the PV module. As in the PVGIS analysis, system losses were neglected. The same model (Figure 1) was simulated using nine different EPW files corresponding to the analyzed locations. For the assessment of shading effects, an additional model was made (Figure 2), in which the impact of the surrounding object was represented based on the actual building geometry. Both models were made using the SketchUp software.

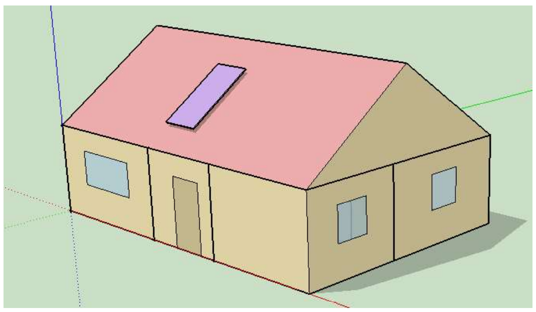

Figure 1. 3D model of the fixed roof-mounted PV system

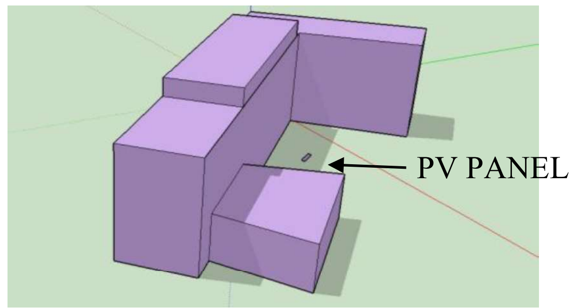

Figure 2. 3D model used for shading simulation

The outcomes of the simulations are presented and discussed in the next section.

3. Results and discussion

3.1. Comparison of PV energy production across locations

The PV energy production for nine representative locations in Serbia was simulated using EnergyPlus, and both PVGIS datasets, applying identical input parameters as described in the Methodology section. The results are summarized in Tables 2-7, which present both the monthly and the annual PV energy production as well as the corresponding differences between the models. Tables 2-4 show the comparison between EnergyPlus and PVGIS-SARAH, while tables 5-7 present the comparison between EnergyPlus and PVGIS-ERA5.

In the tables, EPW stands for EnergyPlus simulation results, whereas SARAH3 and ERA5 represent the results from PVGIS simulations using the respective datasets.

3.1.1. EnergyPlus and PVGIS-SARAH3

The results show that the PVGIS-SARAH3 dataset generally predicts lower energy yields compared to EnergyPlus across all analyzed locations. Looking at Tables 2-4, the following range of deviations between two tools is observed: Subotica: from 0.02% (May, December) to 20.22% (January); Novi Sad: from 0.89% (June) to 20.55% (February); Belgrade: from 0.02% (July) to 18.66% (February); Kragujevac: from 0.46% (July) to 17.87% (March); Negotin: from 0.79% (August) to 17.49% (November); Zlatibor: from 4.39% (October) to 27.51% (March); Niš: from 0.26% (July) to 22.07% (January); Vranje: from 0.49% (August) to 21.44% (January); Priština: from -0.45% (July) to 25.93% (January). These results indicate that PVGIS-SARAH3 shows highest correlation with EnergyPlus mostly for summer months, while the highest deviations occur in winter months. When considering the absolute values of monthly deviations, the number of months in which the deviation exceeded 10% can be used as an indicator of the precision of PVGIS-SARAH3 for each location:

Subotica (2), Novi Sad (5), Belgrade (3), Kragujevac (3), Negotin (4), Zlatibor (7), Niš (3), Vranje (4) and Priština (5). It is evident that the majority of these larger deviations occur during winter months, when diffuse radiation dominates and total solar gains are more challenging to calculate. The locations showing the most months with deviations higher than 10% are Zlatibor, Priština and Novi Sad. The mean absolute value of deviations for winter months is 11.07%, while in the summer, when direct irradiance dominates, the tools show a strong correlation, with a mean deviation of 5.05%. When April is excluded, this value decreases further to 3.53%.

Analyzing the mean absolute value of monthly deviations across all locations, Zlatibor again stands out, where the highest overall deviation is observed (13.43%). For satellite-based dataset such as SARAH3, the elevation and complex topography can present a cause for an underestimation of solar irradiance. Similar effect can be observed in the other complex-topography locations such as Kragujevac (7.22%), Niš (8.65%), Vranje (7.13%) and Priština (9.80%). The lowest deviations are observed in the case of Subotica (5.38%), followed by Negotin (6.23%). On the other hand, Novi Sad (8.04%) and Belgrade (6.67%), deviate from this trend, suggesting that other factors, such as atmospheric pollution and differences in the mathematical modeling approach used for irradiance estimation, may also play a role.

Overall, the mean absolute value of monthly deviation across all locations is 8.06%.

3.1.2. EnergyPlus and PVGIS-ERA5

The simulations conducted using the PVGIS-ERA5 dataset demonstrate a much closer correspondence with EnergyPlus results compared to the previous case. Looking at Tables 5-7, the following range of deviation between two tools is observed: Subotica: from 0.56% (October) to 14.29% (December); Novi Sad: from 0.26% (March) to 13.41% (November); Belgrade: from -0.35% (May) to 16.78% (January); Kragujevac: from 0.94% (November) to 16.41% (January); Negotin: from 0.53% (May) to 33.23% (November); Zlatibor: from 0.07% (May) to 13.23% (January); Niš: from 0.71% (February) to 16.57% (December); Vranje: from 0.29% (May) to 12.17% (September); Priština: from 0.02% (February) to 6.23% (December). Similar to the previous comparison, PVGIS-ERA5 shows lowest correlation with EnergyPlus for winter months, while no clear pattern can be established regarding which months produce the strongest agreement. When considering the absolute values of monthly deviations, the number of months in which the deviation exceeded 10% can be used as an indicator of the precision of PVGIS-ERA5 for each location: Subotica (2), Novi Sad (1), Belgrade (1), Kragujevac (2), Negotin (5), Zlatibor (1), Niš (1), Vranje (3) and Priština (0). Once again, the majority of these larger deviations occur during winter months. Interestingly, compared to the previous case where Zlatibor, Novi Sad and Priština showed the most months with deviations higher than 10%, in this case they performed much better. For the other locations the results are very similar to the previous case, while Negotin achieved the worst results.

The mean absolute value of deviations for winter months is 7.05%, while for the summer period it is 3.60%, indicating a strong overall correlation between the two models. Analyzing the mean absolute value of monthly deviations reveals that Negotin again stands out, with the highest overall deviation across all locations (11.24%). Interestingly, this time, the lowest deviations are observed in the case of Priština (3.37%) and Zlatibor (3.47%), which in the previous comparison showed the highest deviations. The results for remaining locations range between 4.09% (Novi Sad) and 5.56% (Niš).

Although PVGIS-ERA5 and EnergyPlus show generally strong correspondence, among the factors discussed in the previous comparison, the difference in results (especially Negotin), can be explained by the possible variations in the location of the meteorological station. The ERA5 has a spatial resolution of 0.25° lat/lon, representing the coverage of 25 km^2 on the map [17]. Additionally, the exact location of the ERA5 meteorological station is not familiar, which may lead to differences when compared to EnergyPlus. Considering these two factors, it can be concluded that the differences in results are possibly correlated with the variations between the two meteorological datasets used, among other factors.

Overall, the mean absolute value of monthly deviation across all locations is 5.32%.

Table 1. Monthly PV energy production obtained from EnergyPlus (EPW) and PVGIS (SARAH3) for nine analyzed locations, with comparison- part 1

Month	SUBOTICA			NOVI SAD			BEOGRAD		
	EPW [kWh]	SARAH3 [kWh]	Difference	EPW [kWh]	SARAH3 [kWh]	Difference	EPW [kWh]	SARAH3 [kWh]	Difference
Jan	44.12	35.2	20.22%	44.69	36.3	18.78%	40.72	38.32	5.89%
Feb	49.94	46.44	7.02%	59.41	47.2	20.55%	59.25	48.19	18.66%
Mar	87.44	75.69	13.44%	84.44	73.85	12.54%	84.49	73.65	12.83%
Apr	93.99	87.87	6.52%	94.71	84.78	10.49%	95.28	83.62	12.24%
May	92.11	92.13	-0.02%	93.01	90.94	2.23%	92.51	90.29	2.40%
Jun	95.72	94.24	1.55%	94.25	93.41	0.89%	91.82	91.77	0.05%
Jul	99.13	102.76	-3.66%	100.30	103.27	-2.96%	101.30	101.28	0.02%
Aug	102.65	98.62	3.93%	99.75	98.62	1.13%	103.41	97.22	5.98%
Sep	81.94	81.48	0.56%	82.55	81.31	1.50%	84.25	80.61	4.32%
Oct	68.34	70.04	-2.49%	66.64	70.32	-5.51%	65.85	70.03	-6.35%
Nov	42.96	45.15	-5.11%	42.99	47.32	-10.06%	46.25	48.37	-4.58%
Dec	31.75	31.75	-0.02%	36.05	32.51	9.81%	36.72	34.24	6.77%

Table 2. Monthly PV energy production obtained from EnergyPlus (EPW) and PVGIS (SARAH3) for nine analyzed locations, with comparison- part 2

Month	KRAGUJEVAC			NEGOTIN			ZLATIBOR		
	EPW [kWh]	SARAH3 [kWh]	Difference	EPW [kWh]	SARAH3 [kWh]	Difference	EPW [kWh]	SARAH3 [kWh]	Difference
Jan	42.27	38.93	7.91%	42.48	39.49	7.04%	49.47	40.81	17.50%
Feb	57.47	47.37	17.58%	54.61	48.86	10.52%	60.59	48.49	19.97%
Mar	86.12	70.73	17.87%	78.17	74.32	4.93%	90.52	65.62	27.51%
Apr	94.19	79.83	15.25%	100.83	86.72	13.99%	90.64	74.15	18.19%
May	92.66	85.75	7.45%	95.88	94.88	1.04%	91.01	81.49	10.46%
Jun	91.89	88.56	3.63%	100.28	96.34	3.93%	91.15	84.87	6.89%
Jul	98.76	99.21	-0.46%	106.78	105.91	0.81%	103.69	93.61	9.72%
Aug	100.53	96.67	3.84%	100.92	101.72	-0.79%	95.77	91.5	4.46%
Sep	82.78	78.84	4.76%	81.99	83.22	-1.50%	81.08	74.97	7.54%
Oct	70.13	68.29	2.62%	61.03	67.43	-10.48%	71.03	67.91	4.39%
Nov	50.91	49.22	3.32%	32.90	38.65	-17.49%	57.17	50.14	12.30%
Dec	36.15	36.85	-1.93%	37.18	38.02	-2.26%	48.50	37.71	22.25%

Table 3. Monthly PV energy production obtained from EnergyPlus (EPW) and PVGIS (SARAH3) for nine analyzed locations, with comparison- part 3

Month	NIŠ			VRANJE			PRIŠTINA		
	EPW [kWh]	SARAH3 [kWh]	Diffe-rence	EPW [kWh]	SARAH3 [kWh]	Diffe-rence	EPW [kWh]	SARAH3 [kWh]	Diffe-rence
Jan	51.55	40.17	22.07%	53.29	41.87	21.44%	55.57	41.16	25.93%
Feb	61.97	51.35	17.14%	63.63	56.76	10.80%	63.09	54.92	12.95%
Mar	80.36	73.61	8.40%	82.72	76.15	7.94%	81.55	74.55	8.59%
Apr	94.98	82.44	13.20%	93.20	84.1	9.76%	96.70	82.92	14.25%
May	95.23	87.84	7.76%	93.35	90.19	3.39%	96.31	89.92	6.63%
Jun	95.45	92.98	2.59%	97.61	96.66	0.97%	98.66	93.16	5.57%
Jul	103.03	103.29	-0.26%	104.21	107.45	-3.11%	103.08	103.55	-0.45%
Aug	98.65	101.27	-2.65%	105.33	104.82	0.49%	104.47	101.82	2.54%
Sep	89.79	81.7	9.01%	96.31	85.87	10.84%	86.47	82.78	4.27%
Oct	76.41	71.2	6.82%	73.65	75.7	-2.79%	74.17	72.37	2.43%
Nov	51.48	49.01	4.79%	54.25	52.34	3.52%	57.59	48.89	15.11%
Dec	39.90	36.26	9.12%	45.75	40.92	10.56%	46.80	37.95	18.90%

Table 4. Monthly PV energy production obtained from EnergyPlus (EPW) and PVGIS (ERA5) for nine analyzed locations, with comparison- part 1

Month	SUBOTICA			NOVI SAD			BEOGRAD		
	EPW [kWh]	ERA5 [kWh]	Difference	EPW [kWh]	ERA5 [kWh]	Difference	EPW [kWh]	ERA5 [kWh]	Difference
Jan	44.12	44.97	-1.92%	44.69	46.63	-4.34%	40.72	47.55	-16.78%
Feb	49.94	55.09	-10.30%	59.41	56.09	5.58%	59.25	57.09	3.64%
Mar	87.44	84.21	3.70%	84.44	84.22	0.26%	84.49	83.38	1.31%
Apr	93.99	92.55	1.54%	94.71	92	2.87%	95.28	91.44	4.03%
May	92.11	94.3	-2.38%	93.01	93.72	-0.76%	92.51	92.83	-0.35%
Jun	95.72	92.02	3.87%	94.25	90.52	3.96%	91.82	90.05	1.92%
Jul	99.13	97.55	1.59%	100.30	98.05	2.24%	101.30	97.34	3.91%
Aug	102.65	95.83	6.65%	99.75	95.4	4.36%	103.41	94.94	8.19%
Sep	81.94	79.9	2.49%	82.55	80.76	2.17%	84.25	80.64	4.29%
Oct	68.34	67.95	0.56%	66.64	68.81	-3.25%	65.85	69.06	-4.87%
Nov	42.96	46.26	-7.69%	42.99	48.76	-13.41%	46.25	50.32	-8.80%
Dec	31.75	36.28	-14.29%	36.05	38.19	-5.94%	36.72	39.54	-7.67%

Table 5. Monthly PV energy production obtained from EnergyPlus (EPW) and PVGIS (ERA5) for nine analyzed locations, with comparison- part 2

Month	KRAGUJEVAC			NEGOTIN			ZLATIBOR		
	EPW [kWh]	ERA5 [kWh]	Difference	EPW [kWh]	ERA5 [kWh]	Difference	EPW [kWh]	ERA5 [kWh]	Difference
Jan	42.27	49.21	-16.41%	42.48	53.82	-26.69%	49.47	56.01	-13.23%
Feb	57.47	58.05	-1.01%	54.61	60.47	-10.74%	60.59	62.56	-3.25%
Mar	86.12	82.37	4.35%	78.17	84.22	-7.74%	90.52	85.44	5.61%
Apr	94.19	90.15	4.29%	100.83	92.98	7.78%	90.64	90.37	0.30%
May	92.66	91.1	1.68%	95.88	96.39	-0.53%	91.01	91.07	-0.07%
Jun	91.89	88.95	3.20%	100.28	94	6.26%	91.15	89.1	2.24%
Jul	98.76	95.62	3.18%	106.78	100.72	5.68%	103.69	95.56	7.84%
Aug	100.53	94.64	5.86%	100.92	98.47	2.43%	95.77	93.38	2.50%
Sep	82.78	79.95	3.42%	81.99	82.75	-0.92%	81.08	79.15	2.38%
Oct	70.13	68.94	1.70%	61.03	67.59	-10.74%	71.03	70.25	1.09%
Nov	50.91	51.39	-0.94%	32.90	43.83	-33.23%	57.17	55.87	2.28%
Dec	36.15	40.83	-12.94%	37.18	45.39	-22.08%	48.50	48.93	-0.89%

Table 6. Monthly PV energy production obtained from EnergyPlus (EPW) and PVGIS (ERA5) for nine analyzed locations, with comparison- part 3

Month	NIŠ			VRANJE			PRIŠTINA		
	EPW [kWh]	ERA5 [kWh]	Difference	EPW [kWh]	ERA5 [kWh]	Difference	EPW [kWh]	ERA5 [kWh]	Difference
Jan	51.55	53.94	-4.64%	53.29	58.89	-10.50%	55.57	57.58	-3.62%
Feb	61.97	62.41	-0.71%	63.63	64.49	-1.35%	63.09	63.08	0.02%
Mar	80.36	84.69	-5.39%	82.72	86.88	-5.03%	81.55	85.81	-5.22%
Apr	94.98	90.6	4.61%	93.20	92.19	1.08%	96.70	93.51	3.30%
May	95.23	92.39	2.98%	93.35	93.08	0.29%	96.31	94.83	1.53%
Jun	95.45	90.91	4.76%	97.61	93.15	4.56%	98.66	94.04	4.68%
Jul	103.03	97.01	5.84%	104.21	99.83	4.21%	103.08	99.63	3.35%
Aug	98.65	97.08	1.59%	105.33	99.99	5.07%	104.47	99.61	4.65%
Sep	89.79	81.88	8.81%	96.31	84.59	12.17%	86.47	83.97	2.90%
Oct	76.41	70.94	7.16%	73.65	74.75	-1.50%	74.17	72.9	1.72%
Nov	51.48	53.33	-3.60%	54.25	56.54	-4.22%	57.59	55.75	3.20%
Dec	39.90	46.51	-16.57%	45.75	50.62	-10.64%	46.80	49.71	-6.23%

3.2. Comparison of PV energy production when shaded

The results illustrating the impact of shading on the simulated PV energy production obtained from both PVGIS (both datasets) and EnergyPlus are presented in Table 8.

Table 7. Annual PV energy production under shaded conditions considered for Kragujevac, simulated using EnergyPlus, PVGIS-SARAH3 and PVGIS-ERA5

Shading	EPW [kWh]	SARAH3 [kWh]	ERA5 [kWh]	EPW vs SARAH3	EPW vs ERA5
Kragujevac	307.41	840.87	893.39	63.44%	65.59%

The results clearly show that PVGIS lacks the capability to account the impact of the shading on the PV energy production. While PVGIS estimates annual energy yields of 840.87 kWh using the SARAH3 dataset, and 893.39 kWh using the ERA5, the EnergyPlus simulation predicts a significantly lower value of 307.41 kWh, that is, 63.4% and 65.6% lower than PVGIS-SARAH3 and PVGIS-ERA5, respectively. This highlights a major limitation of the PVGIS tool, significantly restricting its applicability in scenarios where PV modules are partially or periodically shaded.

4.Conclusion

This study presented a comparative analysis between the EnergyPlus simulation software and the PVGIS web application, using both SARAH3 and ERA5 datasets for assessing the energy performance of photovoltaic (PV) systems across multiple locations in Serbia. The main objective was to evaluate the level of correspondence between the two tools and determine the applicability of PVGIS for reliable energy yield estimations. Simulations were conducted under identical input conditions for both tools, firstly in unshaded conditions, and secondly with shading applied. Based on these simulations, several conclusions were drawn.

The analysis revealed that deviations between the two tools are not uniform across locations. They vary depending on climatic and geographical factors, terrain complexity, atmospheric pollution, differences in mathematical models used, and possibly on the position and characteristics of the meteorological stations providing input data. The monthly analysis revealed that the largest deviations consistently occur during the winter period. This is primarily attributed to the dominance of diffuse solar radiation. On the other hand, during summer months, when direct irradiance prevails, both datasets showed a strong correlation with EnergyPlus.

Between the two PVGIS datasets, ERA5 provided results that are in better agreement with EnergyPlus simulations. The mean absolute value of monthly deviations across all locations was 5.32% for ERA5, compared to 8.06% for SARAH3. However, even with ERA5, location-specific differences remain (Negotin example), indicating that the spatial resolution may lead to inaccurate assumptions, thus reducing its consistency in providing precise data.

Furthermore, the analysis of shaded scenarios revealed a significant limitation of the PVGIS tool: its inability to account for the impact of shading on PV system performance. The comparison with EnergyPlus demonstrated that PVGIS significantly overestimates energy production under shaded conditions, with deviations exceeding 60%.

In conclusion, the PVGIS software can be used for quick evaluations and rough calculations, especially for unshaded locations, while for the more precise results, advanced engineering software, such as EnergyPlus, should be used.

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