ORIGINAL PAPER

SIMULATED *vs*. PRODUCED ELECTRICAL ENERGY OF A 9.6 KWP PV SYSTEM INSTALLED IN A TEMPERATE MOUNTAIN CLIMATE

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Abstract. *The paper presents a comparative study between three PV simulation software – PVsyst, PVGIS - Photovoltaic Geographical Information System and PVwatts – regarding the monthly and yearly electrical energy production in a temperate mountain climate. As a case study, the obtained simulation results were compared with the experimental data of a 9.6 kWp PV system installed in Brasov, Romania. This study highlights that, in the considered assumptions, the PVGIS tool generates the most accurate values if three solar radiation datasets (CMSAF - Satellite Application Facility on Climate Monitoring, SARAH - Surface Solar Radiation Data Set - Heliosat and COSMO - COnsortium for Small-Scale Modeling) are combined. Also, good results are obtained using the PVsyst tool, where the system parameterisation can be detailed more accurately.*

Keywords: *PV system, electrical energy production, simulation software, experimental result, temperate mountain climate.*

1. INTRODUCTION

Fossil fuels are currently the most used sources of energy. Due to their unequal and limited distribution on Earth, the access to them is constantly a source of political and military conflict and economic speculation. This is why the use of renewable energy resources locally available (like solar, wind and hydro energy) is an importation key in lowering these conflicts and a major step towards the development of sustainable communities.

Estimating the renewable energy potential in a specific location or for large areas (regions, countries or even continents) is an important issue for assuring an optimal transition from the classical non-renewable energy mix to a more sustainable mix based on renewable energy systems and especially on the use of solar energy converters (photovoltaic and solar-thermal) [1].

Further on, the accurate assessment of the solar energy [2] and photovoltaic potential [3] is a key issue for appropriate energy policies and solutions suited to the specific conditions of the region [4]. The most accurate estimation of the local solar potential requires continuous monitoring over several years using specialized equipment, which is both costly and time-consuming. Another possibility is the use of meteorological datasets, which combined with simulation tools are able to predict the energy output of photovoltaic systems.

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Several software tools are available on the market for estimating the performance of photovoltaic systems in different parts of the Earth. Some of the most used tools are PVsyst, PVGIS, PVwatts, PVSol, SolarGIS (Solar Geographical Information System), Homer, as indicated in [5]. Recent studies on the photovoltaic potential based on the use of software tools are available in literature for different countries, which generated implementation recommendations for photovoltaic plants on a large scale [6-8].

Most of these tools are also capable of estimating the available solar energy in a location based on own or imported databases, estimation models or satellite data. Their forecasting accuracy is analysed in the literature. Huld et al. [9] showed an overall Mean Bias Error of +2% using the CMSAF data in PVGIS compared to the data from 20 real solar monitoring stations, but also lower values in the Alps, Carpathians and parts of Romania, compared to the previous versions of PVGIS. A close fit between solar radiation estimated based on satellite data and ground measurements is also indicated in [10].

The simulation tools have different accuracy in estimating the solar potential and photovoltaic production. The selection of an appropriate simulation software suitable for a given implementation location is a challenging issue; one solution is to use several tools and cross-analyse their results. In this way, the tools which generate the highest deviations compared to the rest of the tools can be eliminated. As an example, the generated photovoltaic energy and the performance ratio is analysed by Dondariya et al. [11], for a 6.4 kWp grid-connected PV system in Ujjain, India, using PV*SOL, PVGIS, SolarGIS and SISIFO. The obtained results indicate that SISIFO overestimates the energy production for the considered location, compared to the other three tools.

An even more precise validation of the simulation tools accuracy can be obtained if the simulated results are compared with the energy produced by real photovoltaic systems. As such, the annual energy produced by a 10MW grid-connected photovoltaic system installed in Ramagundam, India (humid subtropical climate) is compared with the simulated results obtained using PVsyst and SolarGIS tools [12]. The actual energy produced was roughly 15.606 MWh/year while PVsyst and SolarGIS overestimated the production with approx. 3% and 6%, respectively.

The analysis of another PV system (190 kWp) in the tropical wet and dry climate (Khatkar-Kalan, India) indicates even more precise estimations when using measured solar radiation data: the real PV energy production was 154.43 MWh during the year 2011, while PVsyst estimated it by 1.4% more [13].

Since in literature the most research work has been devoted only to comparative studies between measured and simulated data from the tropical and subtropical climate, the current paper focuses on the use of simulation tools in the European temperate climate.

Thus, the accuracy and usefulness of photovoltaic simulation software able to estimate the photovoltaic energy production are further analysed. Two well-known online tools (PVGIS, PVwatts) and offline software (PVsyst) were selected and their simulation results were compared with real experimental data obtained from a 9.6 kWp PV system, installed in the built environment of a mountain region, situated in the temperate climate (Brasov, Romania).

The paper describes in the first part the experimental and the simulation setup, while in the second part uses the obtained data for drawing recommendations regarding the appropriateness of the tested tools for mountain sites located in a temperate climate.

2. EXPERIMENTAL SETUP

The PV system used in this work is among the first of its kind installed in the considered region and was commissioned at the beginning of 2008 [14]. It consists of 48 photovoltaic modules, type Energy Solutions, model ES200W with the following characteristics: nominal power P_{mp} = 200 W ± 5%; voltage at maximum power point V_{mp} = 27.7 V; current at maximum power point I_{mp} = 7.3 A; short-circuit current I_{SC} = 7.8 A; open-circuit voltage V_{OC} = 35.8 V.

The 48 PV modules are physically divided into three equal groups of 16 modules (Fig. 1), installed on platforms tilted at 48° from the horizontal plane and oriented 20° from South to the West.

Figure 1. On-grid 9.6 kWp photovoltaic system installed on the Colina Hill rooftop facilities of the Renewable Energy Systems and Recycling R&D Centre, Transilvania University of Brasov.

The PV system is connected to the local grid using three inverters, each of them connected to a different power line, as indicated in Fig. 2. Two of the inverters are SMA SunnyBoy SB 3300 model (nominal power P_{nom} = 3300 W), converting the energy produced by 2 parallel strings of 10 PV modules. The third inverter is SMA SunnyBoy SB 1700 model (P_{nom} = 1550 W) and delivers the energy produced by a string of 8 PV modules to the grid.

The PV system is monitored using a SMA *Sunny Control* device connected to the online SMA *Sunny Portal*. The daily energy production data from each inverter, extracted using the monitoring system, is considered in the paper for a time interval between January 2016 and October 2019.

The DC to AC size ratio of the SB 3300 inverters is 1.21, of the SB 1700 inverter is 1.03, while for the entire system the ratio is 1.18. Despite this fact, no power cut-offs were observed during the analysed interval. This can be attributed to: (a) the aging of the modules (approx. 10 years), (b) the limitation of the collected solar energy during intervals with high available solar energy due to the high value of the tilt angle, and (c) the high working temperature of the PV modules during these intervals determined by the back-cover of the modules used for protecting them against possible damage from the winds.

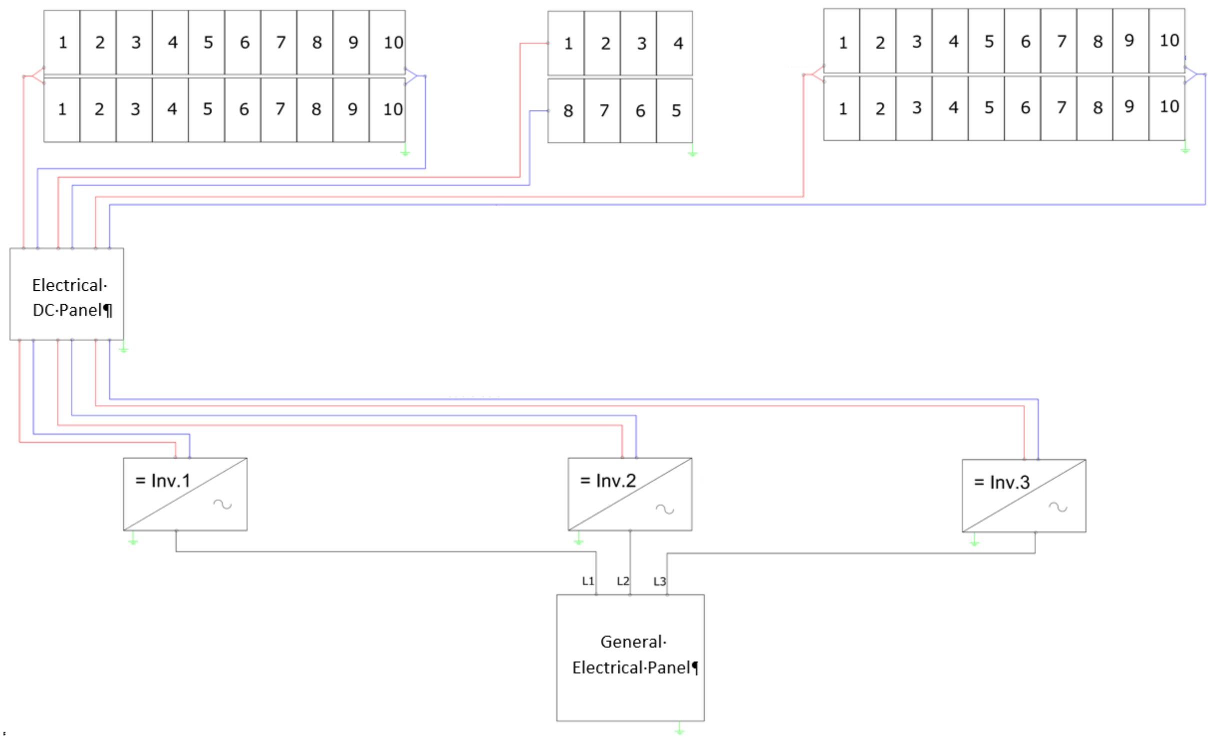

Figure 2. Electrical connections of the 9.6 kWp photovoltaic system.

3. SIMULATION SETUP

Three common simulation tools (PVsyst, PVGIS and PVwatts) were considered in the paper in order to generate electrical energy production data of a similar PV system to the one already implemented at the Transilvania University of Brasov. Further, the three tools are summarily described.

PVsyst is a dedicated offline software for analysis of PV systems, widely used throughout the world for sizing, simulation and prefeasibility studies, being considered a reference tool in the PV industry. It was developed during the mid-1990s by the Energy Group at the University of Geneva, Switzerland and regularly updated since then.

The input data regarding the available solar radiation and meteorological conditions in the tested location can be obtained from various sources: NASA (National Aeronautics and Space Administration), Meteonorm, PVGIS or other data can be used if hourly values are available.

The software contains a database with PV system components (photovoltaic modules, inverters, charge regulators, batteries, etc.) produced by different manufacturers from which the user can select the appropriate ones or add any extra needed parts. It allows the detailed adjustment of the PV components and the electrical loads parameters, as indicated in Table 1. A 3D shading analysis of the PV system can also be obtained if the PV structure is drawn together with the surrounding elements, such as nearby buildings, electricity masts or high vegetation. PVsyst allows a detailed adjustment of the simulated system so that this can be well fitted to the experimental PV system.

PVGIS is a web-based application (https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html) able to estimate the performance of PV systems installed in Europe and Africa. It was developed and is continuously upgraded by the Joint Research Center of the European Commission (Ispra, Italy).

PVGIS uses four data sources for estimating the solar radiation, according to the developers: CMSAF is a dataset developed by Eumetsat that covers Europe, Africa and parts of South America; SARAH dataset is based on a new algorithm developed by CMSAF that also covers Asia. In addition to the mentioned datasets, for Europe, ERA5 dataset is made available by the European Centre for Medium-Range Weather Forecast (ECMWF), and COSMO dataset is taken from the COSMO-REA regional reanalysis (https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html).

PVwatts is also a web-based application (https://pvwatts.nrel.gov/pvwatts.php) that estimates the electricity production of a PV system for any location worldwide. It was developed by NREL (National Renewable Energy Laboratory, USA) in 1999 and updated regularly.

It uses hourly typical meteorological year (TMY) data for the selected location from different data sources: NREL National Solar Radiation Database (NSRDB) for US, while for other locations outside of the US other three sources are used: Solar and Wind Energy Resource Assessment Programme (SWERA), ASHRAE International Weather for Energy Calculations Version 1.1 (IWEC) and Canadian Weather for Energy Calculations (CWEC).

The main adjustable parameters in the three simulation tools described above are given in Table 1. Each of the used simulation tools allowed to configure the simulation input parameters according to the experimental setup: PVsyst using detailed parameters, while PVGIS and PVwatts only general ones.

Table 1. Adjustable parameters available in the considered simulation tools.

Parameter name	**PVsyst**	**PVGIS**	**PVwatts**
General parameters			
Location	x	x	x
PV technology	x	x	x
Tilt angle	x	x	x
Azimuth angle	x	x	x
Mounting type	x	x	x
Overall system losses	-	x	x
DC to AC size ratio	x	-	x
Inverter efficiency	x	-	x
Detailed parameters			
PV module editing	x	-	-
PV string configuration	x	-	-
Horizon editing	x	x	-
Detailed system losses	x	-	-
Inverter editing	x	-	-

All the three tools allow the selection of the location according to the precise implementation location at the Transilvania University in Brasov (45.655°N, 25.597°E).

The PV modules used in the simulation were detailed in PVsyst which allowed the adjustment of all parameters [15], while PVGIS allowed only the selection of the PV technology (*crystalline silicon*, CIS and CdTe) and PVwatts allowed only the selection of the module type (*standard*, premium or thin-film).

Regarding the losses of the PV system, the configuration possibilities are similar. PVsyst allows the detailed adjustment of different losses types (among them the aging of the modules was configured to decrease the conversion efficiency with 0.4%year, and the soiling due to impurities and snow was considered 10% during the winter months December-

February, 5% during November and 1% during the rest of the year). PVGIS and PVwatts allowed only the selection of the overall system losses; the predefined value 14% was chosen.

The mounting type of the modules was selected so that it is similar to the back-cover of the modules in the experimental setup, which generates an over-heating effect. In PVsyst the option called *integration with fully insulated back* was selected, while in PVGIS the option called *building-integrated* and in PVwatts *fixed with roof-mount* were considered.

The tilt angle and the azimuth angle were selected in all three tools as the ones of the experimental PV system: 48° from the horizontal plane and oriented towards West 20° from the South direction.

Horizon editing is another parameter which can be adjusted only in PVsyst and in PVGIS. While in PVsyst the horizon can be edited only if the local implementation location is analysed, PVGIS is able to determine the horizon profile from the selected implementation. Thus in the simulations used in this paper, only PVGIS considered the local horizon.

A detailed configuration of the strings used in the experimental PV system is possible only in PVsyst; here, the number of PV modules and the detailed parameters of the inverters used in each string can be defined. PVwatts enables the user to define only the DC to AC size ratio, 9600/8150 in the case of the experimental system, and the overall efficiency of the inverter, considered by default 96%. On the other hand, in PVGIS no configuration of the PV strings and inverters is possible.

4. RESULTS AND DISCUSSION

The comparative analysis of the monthly, seasonal and annual estimation of the electrical energy produced by a photovoltaic system for the urban environment in the temperate mountain area is performed considering three software products specialised in the design of photovoltaic systems: PVsyst, PVGIS and PVwatts. The results obtained with these tools are further presented with reference to the electricity production during 2016-2019, of a 9.6 kWp PV system installed in the RESREC R&D Centre, Brasov.

The monthly electricity production provided by the 9.6 kWp PV system, Fig. 3, is characterized by significant variations of the monthly values for the analysed years, especially during the winter months (e.g. January) and the transitional seasons (e.g. March and October). This variability is specific to the temperate mountain climate, for which significant variations of the meteorological parameters that are important for the operation of a photovoltaic system (e.g. solar radiation, temperature and precipitation) [16] can be recorded in different years.

Thus, the electricity production in 2016 was of 9604 kWh, in 2017 of 10198 kWh, and in 2018 of 9963 kWh, with a maximum relative deviation of about 3.2% compared to the average value of 9922 kWh/year for the three years. The highest relative deviation from the average value is recorded for the winter season (approx. ±14.5%) and the lowest for the summer season (approx. ±6.5%); during the transient seasons, the relative deviation is approx. ±7.5%. The annual production registers relative variations within the limit of 3-4% as a result of the unpredictable variation of meteorological parameters.

The monthly average values of the electricity produced during 2016-2019, further denoted by *Exp. avg*, are depicted in Fig. 3. As expected, the minimum value is recorded in December, and the maximum in August - generally the month with the highest level of solar energy. These average experimental values are further considered in the comparative analysis with the values estimated by using the three software products.

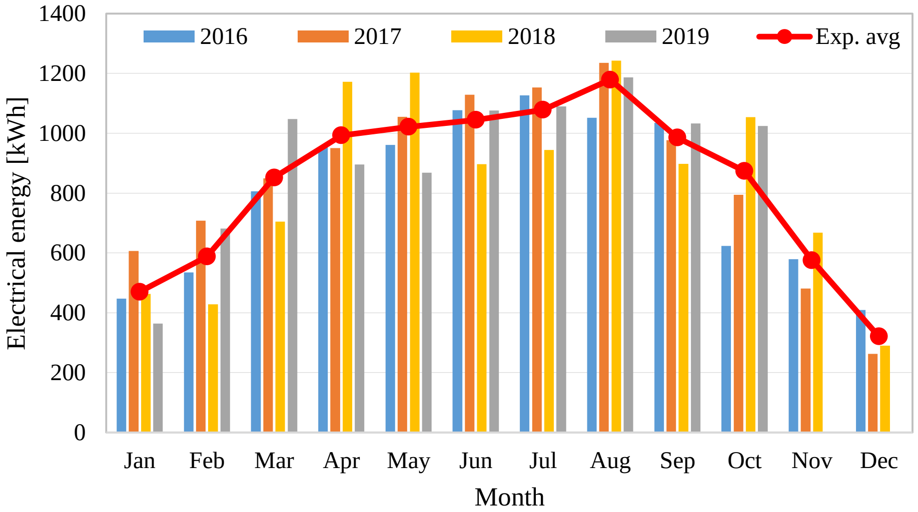

Figure 3. Monthly and average values of the electrical energy produced by the 9.6 kWp photovoltaic system during 2016…2019.

The PVsyst software allows the use of several databases to generate the weather profile of a location, mainly Meteornorm and NASA. The use of the two datasets to simulate the electrical response of the 9.6 kWp system has led to significant differences between them regarding the monthly and yearly electricity production (Fig. 4). Both datasets significantly underestimate electricity production in August and overestimate it during the cold season (October-March). Comparatively, the Meteonorm dataset better fits the experimental results and is therefore preferred to the NASA database for the Brasov location.

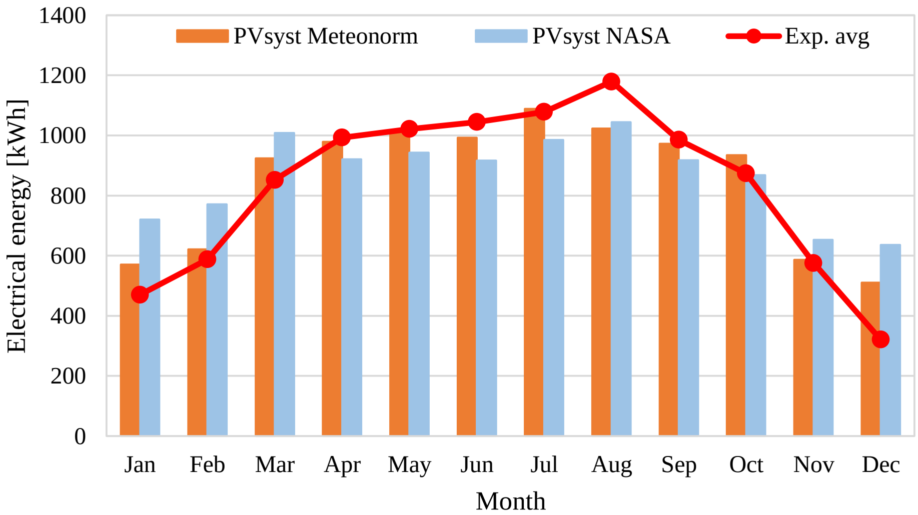

Figure 4. Experimental vs. estimated monthly electrical energy by using the Meteonorm and NASA meteo databases in the PVsyst software.

The CMSAF, SARAH and COSMO datasets from PVGIS lead to relatively close simulated results, slightly different from the experimental ones. Contrary, the ERA5 method overestimates the production in all months of the year compared to the experimental results (Fig. 5). The first three methods generally lead to an underestimation of electricity production in the warmer period (April-October) and an overestimation in the colder period (November-March). In these conditions, for analysing the results of the simulations with the experimental ones, a possible and rational solution is to consider the average values resulting from the CMSAF, SARAH and COSMO methods (denoted by *PVGIS avg*, Fig. 6).

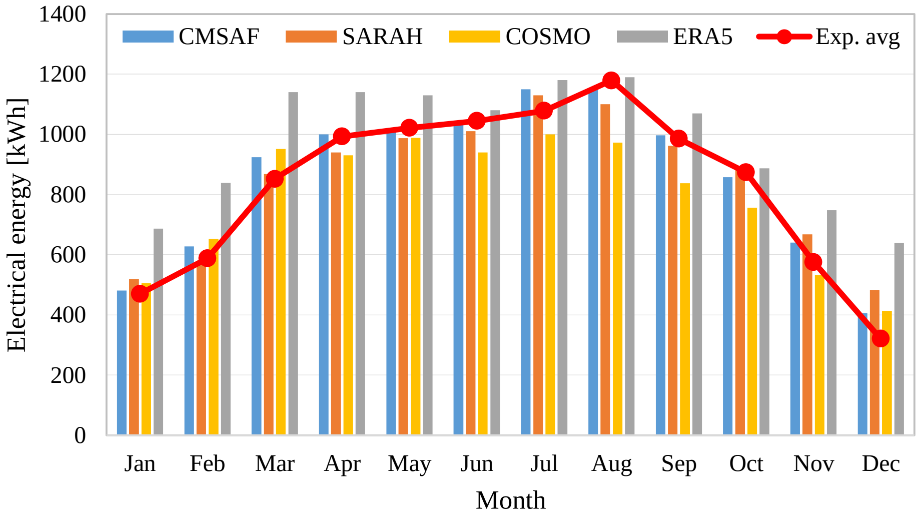

Figure 5. Experimental vs. estimated monthly production of electrical energy by using the PVGIS software.

In contrast to PVsyst and PVGIS, the use of PVwatts leads to results significantly different from the experimental ones (Fig. 6), especially during the interval of May-August, for which an overestimation of up to 35% of the electricity production was obtained. According to the seasonal and annual data obtained experimentally and from the simulation tools, presented in Table 2 based on the results shown in Fig. 6, *PVGIS avg* is the most suitable approach, followed closely by PVsyst Meteonorm simulation. PVsyst and PVGIS generate accurate electricity production results during spring and autumn seasons, good estimations during the summer and less accurate during the winter (Table 2).

The PVwatts method can be excluded, leading to annual deviations of more than 13%, well above the uncertainty level of 3-4% of the actual annual electricity production for the Brasov location. The best performance of PVwatts is observed during winter and autumn, while high deviations are obtained during summer and spring and lead to the high annual inaccuracies of this tool.

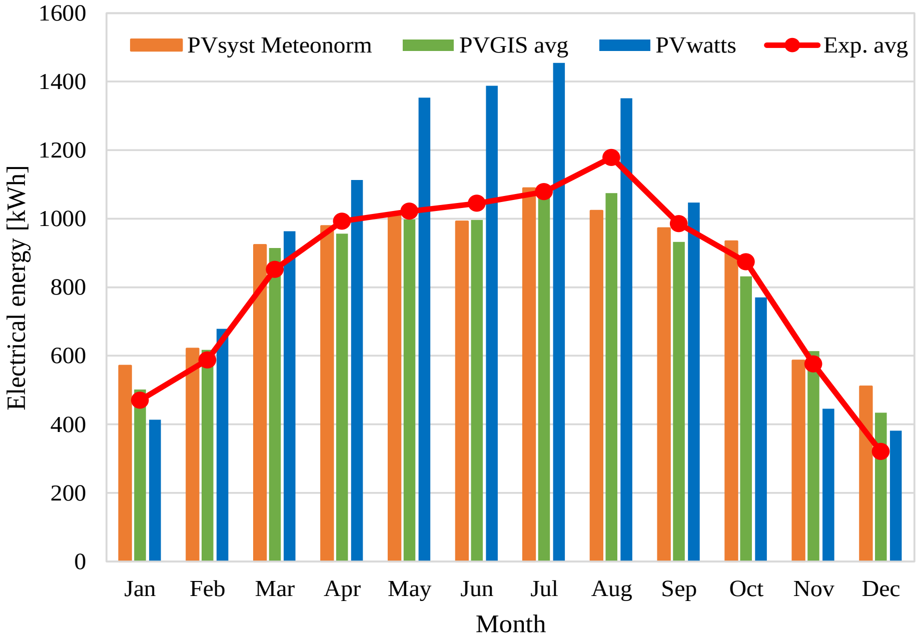

Figure 6. Experimental vs. estimated monthly electrical energy results by using PVGIS, PVwatts and PVsyst.

Table 2. Produced vs. simulated seasonal and yearly electrical energy.

	Electrical energy [kWh] and its relative deviation from the average experimental electricity production (%)				
	Winter	Spring	Summer	Autumn	Total
Exp. avg	1379	2866	3302	2435	9981
PVGIS avg	1553 (12.7%)	2869 (0.1%)	3164 (-4.2%)	2378 (-2.3%)	9965 (-0.2%)
PVsyst Meteonorm	1703 (23.5%)	2918 (1.8%)	3104 (-6.0%)	2493 (2.4%)	10218 (2.4%)
PVwatts	1474 (6.9%)	3429 (19.6%)	4194 (27.0%)	2263 (-7.1%)	11360 (13.8%)

5. CONCLUSIONS

The paper presents a comparative study of the electrical response generated using three specialized photovoltaic estimation software, for fixed tilted PV applications in the urban environment from temperate mountain areas. The validation of the simulated results for the Brașov location in Romania was achieved using the experimental data recorded in the interval 2016-2019 from a 9.6 kWp PV system installed in the RESREC R&D Centre, Transilvania University of Brasov. The simulation and experimental results obtained for this case study allowed the following conclusions to be drawn:

- although PVGIS and PVwatts are mainly recommended for preliminary studies on the performance of photovoltaic systems, the numerical results obtained from PVGIS indicate a very good correspondence between simulated and experimental data if the average values obtained using the CMSAF, SARAH and COSMO datasets are considered. Thus, PVGIS is sufficiently accurate in the monthly and yearly estimation of the electrical energy with only several summary setup data;
- PVsyst allows the most detailed setup of the PV system parameters, according to the PV application specifications, and may become very accurate in estimating the electricity production if local meteorological data are used;
- the current version of PVwatts is the least recommended for estimation of electrical energy production in PV applications located in mountain areas with a temperate climate.

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