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Review Article

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Review and validation of photovoltaic solar simulation tools/software based on case study

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Abstract: Photovoltaic (PV) systems are an excellent solution to meet energy demand and protect the global environment in many cases. With the increasing utilization of the PV system worldwide, there is an increasing need for simulation tools to predict the PV system's performance and profitability. This research includes testing and comparison of PV tools: photovoltaic geographical information system (PVGIS), PVWatts, SolarGIS, RETScreen, BlueSol, PVsyst, HelioScope, PV*SOL, Solarius PV, Solar Pro, PV F-Chart, PolySun, solar advisor model (SAM), and hybrid optimization model for electric renewables (HOMER), based on experimental data obtained from fixed on-grid 2 kW_p PV system in 2019. The PV system is part of a research project related to the examination of the PV system operation in real climatic conditions in Niš. This research investigates the most appropriate PV software for PV systems design by testing the most commonly used PV tools. It was accomplished by comparing experimental data obtained by a 2 kW_p PV system in Niš and estimated data obtained from different PV tools. The study shows that annually, the experimentally measured average daily solar irradiation on the inclined plane was 5,270 Wh/m^2/day, and the lowest deviation of the simulation results compared to experimental measurements was obtained by SolarPro. Total annual electricity production from the given system was 2455.621 kW h, and the lowest deviation of the simulation results compared to experimental measurements was obtained by PVGIS. By analyzing and publishing the actual solar irradiation and PV power output data, this study could help researchers to increase the PV systems modeling accuracy.

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Keywords: PV simulation tools/software, Solar Pro, PV*SOL premium, Helioscope, BlueSol, PV F-Chart, PolySun, Solarius PV, solar databases, on-grid PV system

Abbreviations

AC	alternating current
CF	capacity factor
CMSAF	climate monitoring satellite application facility
CPV	concentration photovoltaics
DC	direct current
GHG	greenhouse gas
HIT	heterojunction with intrinsic thin layer
HOMER	hybrid optimization model for electric renewables
mj	multi-junction
NSRDB	national solar radiation database
NREL	national renewable energy laboratory
POA	plane of array
PR	performance ratio
PV	photovoltaic
PVGIS	photovoltaic geographical information system
RES	renewable energy sources
SAM	solar advisor model
SARAH	surface solar radiation dataset-heliosat
STC	standard test conditions
SWERA	solar and wind energy resource assessment
TMY	typical meteorological year
G_{opt}	monthly average daily solar irradiation on south-oriented and optimally inclined plane (kW h/m^2/day)
δ_{Gopt}	relative deviation of monthly average daily solar irradiation on south-oriented and optimally inclined plane (%)
E_e	monthly PV electricity production (kW h)
δ_{Ee}	relative deviation of monthly PV electricity production (%)
L_{yearly}	annual mean values of total energy loss from the given PV system (h/day)

1 Introduction

Photovoltaic (PV) technology was earlier used mainly in space programs or remote locations and was marginalized. Recently it has been gaining ground, becoming a basic technology for the production and distribution of electrical energy in urban areas with the potential to become, in terms of costs, equally competitive with the costs of energy generated and distributed by the conventional technologies. Lately, the industry of PV conversion of solar irradiation shows constant annual economic growth, and total installed PV capacities worldwide have surpassed more than 1,000 MW and more than a million households are using electrical energy generated utilizing the PV systems [1,2]. PV systems modeling influences many aspects of PV application and it is a key step for determination, financing, and PV project implementation. A larger number of software packages were created for predictions of the PV systems' operations to maximize renewable energy source (RES) use. PV tools require many input data such as geographical location (geographical coordinates), local meteorological conditions, solar irradiation, and the planned systems' technical characteristics. Each PV software uses different types of input data and calculation methods. Some of them are created explicitly for energy analysis, while some include financial and greenhouse gas (GHG) analyses [1–4].

This work aims to evaluate 14 PV simulation tools, give insight into the experimental analysis of PV system operation in Niš, and compare the experimental data and estimated data obtained from different PV simulation tools. Considering that the large share of PV system energy output estimation is derived from the solar radiation data, special attention is focused on solar databases which include data of solar irradiation on a PV panel surface (Plane of Array [POA] irradiation) used by the software described in this study. The presented results can also be used for making investment decisions in Serbia's RES sector. This work gives a comparison of the PV systems' simulated and real PV electricity produced in actual meteorological conditions. The results can also be applied in the PV studies and projects to predict electricity production, starting with real energy generation and solar datasets.

1.1 Background

Lately, the EU Energy Community intensively spreads the market across Europe, especially to the southeast, relying on legally binding agreements, and Serbia has been dedicated to implementing acts and laws related to the energy sector. In this regard, Serbia has to align with the EU energy models and regulations [5]. In recent years, the Serbian Government has advanced in that aspect by adopting several legislations to improve RES energy production's feasibility.

The total available technical solar potential in Serbia is 0.24 Mtoe/year. The technically usable energy potential for the solar energy conversion into thermal energy (for hot water preparation and other purposes) is estimated at 0.194 Mtoe/year, assuming the use of solar thermal collectors at 50% of available facilities in the country. Besides, research in the thermal conversion of solar radiation occurs at several facilities in Serbia and is more common than research in the field of PV conversion. Based on the currently available capacities of the electric power system of the Republic of Serbia for providing tertiary reserves, it was adopted that the maximum technically usable capacity of PV power plants is 450 MW, *i.e.*, their technically usable potential is 540 GWh/year (0.046 Mtoe/year). Almost all existing PV capacities in Serbia were built within the feed-in tariff system (FIT), which entered into force in 2009. The first quota under the FIT policy was set at 5 MW and later increased to 10 MW. The 10 MW quota is divided into 2 MW for small roof PV systems (below 30 kW), 2 MW for larger roof PV systems (up to 500 kW), and 6 MW for ground PV systems. Serbia's current total installed PV capacity is 8.82 MW within the FIT scheme (107 PV projects in total) of which 5.34 MW are ground installations, and 3.476 MW are roof installations. Thus, the 10 MW quota has not yet been fully reached. Based on the abovementioned data, Serbia has made progress in the RES energy sector, but the solar potential in Serbia is still underutilized [5,6].

Accordingly, this work is significant for the wider grid-connected PV systems application and provides useful information to customers and companies to invest in and develop the PV market in Serbia and in regions with similar climates. Besides, by analyzing the actual solar irradiation and PV power output data, and comparing with simulation data, this work could help researchers and developers to increase the PV systems modeling accuracy.

2 A review of PV software

In this section, the basic description of PV tools such as Solarius PV, solar advisor model (SAM), PVsyst 6.8.6, PVWatts, photovoltaic geographical information system 5 (PVGIS 5), hybrid optimization model for electric renewables

(HOMER) Grid, SolarGIS, PV*SOL premium, RETScreen Expert, BlueSol 4, HelioScope, PolySun, Solar Pro 4.6, and PV F-Chart is given.

PVGIS is a free online tool that aims to research and predict solar resources and PV system performance in most countries worldwide. PVGIS provides monthly and annual electricity generation estimates for any fixed or tracking PV systems with crystalline silicon (c-Si), CdTe, or CIS solar modules. The first versions of PVGIS have included ground measurements of solar radiation but the latest versions contain only satellite obtained estimations. Meteorological databases from satellite measurements, PVGIS- climate monitoring satellite application facility (CMSAF), PVGIS-ERA5, PVGIS-surface solar radiation dataset-heliosat (SARAH), and PVGIS-COSMO, were implemented in PVGIS. Solar radiation data for Europe, Asia, and Africa come from PVGIS-CMSAF and PVGIS-SARAH datasets, for US, the data come from the national renewable energy laboratory (NREL)- national solar radiation database (NSRDB), and for the high latitude locations, the data come from reanalysis products (PVGIS-COSMO and PVGIS-ERA5). The latest version, PVGIS 5, was used in this work and PVGIS-SARAH dataset was used in PVGIS 5 simulation. Based on the satellite measurements, SARAH provides solar datasets of the global and direct solar irradiation and the effective cloud albedo. The data are obtained from geostationary satellites – METEOSAT. This data covers the measured period from 2005 to 2016. PVGIS 5 also provides the solar radiation data on optimally inclined surfaces using the model described in this article. More information on the development, modeling, and application of PVGIS can be found in refs. [5,7–14]. Unfortunately, PVGIS does not provide GHG and techno-financial analyses.

SolarGIS is an online simulation tool that predicts PV systems' performance and increases PV systems' assessment certainty. SolarGIS consists of four applications (iMaps, climData, pvPlanner, and pvSpot). *iMaps and climData* provide all solar and meteorological datasets for Europe, Africa, Asia, and Brazil. This application estimates different meteorological and solar data parameters and periods: typical meteorological year, monthly, daily, hourly, and 15- or 30-min values. *pvPlanner* allows designing various PV system types and configurations with c-Si, CdTe, and CIS modules. The high-performance algorithms, implemented in a pvPlanner, provide the calculation of long-term monthly horizontal solar irradiation (global and diffuse), POA radiation, reflected radiation and temperature, modules' surface reflectance losses, losses due to temperature, and irradiance, shading by terrain, electricity generation, and performance ratio. PV system performance evaluation and monitoring are provided by *pvSpot*. SolarGIS methodology includes three different models: "Temperature," "Solar irradiation," and "PV power" models. The solar radiation model uses geostationary satellites data and meteorological models data. The air temperature model is based on global meteorological models. The module temperature is estimated based on ambient temperature, effective POA, thermal coefficient, and solar module efficiency. In this research, the solar data for Serbia is provided by the Global Solar Atlas 2.0, which SolarGIS has prepared. These data are estimated from Meteosat Prime and IODC satellite measurements from 1994 (2000) to the present. Air temperature is calculated from atmospheric models (European center for medium-range weather forecasts and national centers for environmental prediction) and POA calculations are based on Perez model. PV system performance model unites statistically aggregate solar and meteorological data, one-diode equivalent circuit model with a five-parameter model (De Soto, 2006) for PV array performance calculations, and Sandia Inverter Model for direct current (DC) to alternating current (AC) losses calculations. SolarGIS does not support GHG and financial analyses and advanced shading analysis [7,15–18].

PVWatts, based on the PVForm algorithms, is an online simulation tool for the modeling and operation predictions of all types of grid-connected (roof- and/or ground-mounted) PV systems. Based on basic PV design parameters, PVWatts assesses PV system electricity production on a monthly level applying an hour-by-hour simulation over 1-year and an electricity's monetary value based on a yearly average retail electricity rate. PVWatts is applied for the PV system performance assessment that uses crystalline silicon or thin-film PV modules. PVWatts uses hourly typical meteorological year (TMY) database from the NSRDB. For locations outside of the NSRDB area, PVWatts uses the weather data available from the nearest NREL International weather station. For other sites outside of the US, the NREL International data sources are solar and wind energy resource assessment (SWERA), ASHRAE IWEC Verse 1.1, and Canadian Weather. For the determination of the POA beam, sky diffuse, and ground-reflected radiation, PVWatts used the Perez algorithm [3,4,7,13,19–23].

RETScreen is a software for different RES systems energy evaluation, financial investment assessments, and environmental impact analysis but cannot model hybrid systems. RETScreen contains a separate "*PV Model*" that allows simulating the PV systems operations worldwide. This tool integrates many databases, such as a meteorological database, project database, cost database, RES components' database, *etc*. RETScreen Expert, used in this work, allows analysis that includes a total project life-cycle and comparing the various types of RES energy performance with a calculated and/or measured monthly energy utilization. RETScreen assesses the performance of different PV technologies that include c-Si and thin-film (CdTe, CiS, and a-Si). On the other hand, RETScreen does not consider the shading and the temperature effects for PV performance analysis and does not include the influence of dust on the solar panels. RETScreen uses the solar and other weather datasets from ground-monitoring stations or from NASA's satellite meteorological resources. If the specific ground station does not provide data for a given location, RETScreen automatically downloads data from NASA's satellite databases. In this research, solar data are provided from the NASA-SEE database, while other weather data are taken from ground monitoring stations. A ground-based database contains meteorological measurements data collected from over 50 different sources from 1982 to 2006 for over 6,700 sites worldwide. NASA's Satellite Climate Database contains data collected for 30 years starting from 1983 based on satellite measurements. For POA radiation calculations, RETScreen uses simply isotropic clear sky model [3,4,7,13,21,22,24–29].

BlueSol is a software intended for professional PV design, starting from the preliminary producibility estimations to the entire project documentation implementations. This tool supports the technical and financial designing, analyzing, and optimizing every type of PV system (fixed or tracking). BlueSol allows modeling the PV system's behavior in all its components. Solar radiation data are acquired directly from NASA-SSE or PVGIS database. Abilities of BlueSol are direct PV system dimensioning, insertion, and verification of electrical components and cables; integrated CAD system for arranging system components (solar modules, strings, cables, batteries, and inverters); 3D visualization of a layout with shading estimations of the near objects and assessments of solar radiation on PV module surfaces. BlueSol is specifically suitable for calculating and analyzing PV systems' elements, emphasizing the electrical components' characteristics. BlueSol has an extensive library of solar modules and inverters [30,31].

PVsyst is a software intended for any type of PV systems analysis and design. This software allows inputs such as orientation of PV array with the ability of mounting or tracking, PV system components, PV array characteristics, inverter model, battery-pack, *etc*., to simulate several dozens of variables. Based on real PV components' prices, investment conditions, and additional costs, PVsyst provides detailed financial assessments. Based on the PV array parameters, location, and solar modules orientation, PVsyst can calculate the inter-row shading effects. A different soiling factor can also be entered for each month. This software can concurrently model PV systems that consist of more than one size or type of inverter and PV arrays with two different tilt and azimuth angles connected to a single inverter. Using the one-diode PV model, PVsyst calculates performances of c-Si, thin-film, and heterojunction intrinsic thin layer (HIT) solar modules and provides detailed system losses estimations. Based on an interpolation method from the METEONORM DLL or a "closest point" method from the NASA-SSE database, PVsyst provides solar and weather data worldwide. PVsyst has the section that constructs a set of hourly meteo data. In this research, PVsyst used monthly measured data (global and diffuse radiation, wind velocity, and temperature) from Meteonorm 7.2, creating hourly synthesized dataset. Monthly solar irradiation datasets are measurement averages over 1991–2009. The diffuse radiation calculations in PVsyst 6.8.6. are based on the Perez model (1987,1988) [3,4,7,18,21,22,32–39].

HelioScope is a software specifically created for PV system design and analyses. This software has some elements of PVsyst, but design functionality is accomplished by AutoCAD. HelioScope performs energy analysis, including losses due to weather conditions. Besides, HelioScope includes shading and temperature effects, system component efficiencies, wiring, module mismatches, soiling impacts, and aging to carry out PV system performance evaluations with increased accuracy. This tool includes advanced calculations to model every component within the PV array. As simulation results, HelioScope provides hourly values of energy production, weather data, PR, and other PV system parameters. Weather data is integrated as Meteonorm TMY file. In this research, HelioScope used TMY, 10 km Grid, and Meteonorm data. Based on weather data from the Meteonorm, along with the module orientation angle and solar angle calculation, HelioScope calculates the DNI on a module. The PSA algorithm, developed by Blanco and Muriel, is used for the solar angle calculation, Sandia Model is used as a temperature model, and the Perez model is used as the default transposition model. It should be noted that the POA radiation calculation in HelioScope is at the module level. Unfortunately, HelioScope does not provide GHG and financial analyses [4,7,20,21,33,35,40–42].

PV*SOL premium is a software specifically made for the detailed shading analysis of all types of ground-integrated, tracking, roof-integrated, or roof-mounted PV systems with 2D or 3D visualization. This software also provides PV systems' performance and financial analysis assessments. The software's main feature is to consider the shading effects from the nearby objects for each solar module and optimize its coverage. PV*SOL has an extensive library of solar modules and inverters (over 7,500 solar modules and 1,500 inverters). Besides, PV*SOL can assess the implementation of various PV technologies that include monocrystalline Si, thin-film (CiS, a-Si, and CdTe), μc-Si, (HIT), and Ribbon. PV*SOL uses a meteorological dataset obtained by the interpolation method from Meteonorm 7.1 or forms a dataset by "closest point" method using NASA database. POA radiation calculations are based on the anisotropic (Hay and Davies) sky model as a default model, and diffuse radiation calculations are based on the Hofmann and Seckmeyer as a default model. However, users can select other POA calculation models such as Liu and Jordan, Klucher, Perez and Reindl. For the quantity of the reflected radiation determination, an incident angle modifier is used. In this research, PV*SOL premium used Meteonorm 7.1 to provide monthly climatic data. Meteonorm 7.1 provides meteorological data with the averaging period of 1991–2010. For POA radiation calculations, PV*SOL premium used the Hay and Davies anisotropic sky model, and for diffuse radiation calculations, PV*SOL used the Hofmann and Seckmeyer model. Based on the amount of POA radiation and solar module I-U characteristics at standard test conditions (STC), PV*SOL calculates PV array performance while a linear or dynamic temperature model can be selected by the users [3,4,7,18,20,33,43–46].

Solarius PV is a software intended for the technical, economic, and GHG emission analyses of PV systems of any size and type and any boundary condition (near and far obstacles). Solar data are downloaded from Meteonorm or PVGIS databases depending on the selected location. PV system design is achieved by BIM modeling interface. Solarius PV has extensive libraries of all PV system components, time-slots and energy consumption profiles, electricity tariffs, zonal sales, guaranteed minimum prices, *etc.* It provides hourly energy production for the full year, detailed profitability assessment, and the entire PV system's amortization period. Solarius PV also supports 3D modeling and provides operational diagnostics to point out any errors at every step of the PV design. Solarius PV also considers the shading effects projected onto the solar modules by nearby objects and graphically represents shadow interferences. In this research, monthly average daily solar irradiation on a horizontal surface is obtained by Meteonorm 7.1, integrated into Solarius PV. Unfortunately, Solarius PV does not provide any detail on POA radiation calculations [3,7,20,33,45,47–49].

Solar Pro is an advanced PV software with integrated 3D-CAD. Solar Pro can be used to design flat-roof, roof-integrated, ground-mounted, and tracking PV systems. The main functions are shade, I–V curve, power, and financial analysis. An advanced 3D shading analysis is achieved by taking into account solar module I–V curves. The total I–V curve calculations are based on each solar module's electrical characteristics, incoming radiation and temperature data, shading, and other loss factors. Solar Pro estimates hourly DC power output and PV system power output, including temperature effects, shading, electrical losses, and soiling. Temperature effects depend on ambient temperature, incoming radiation, and wind speed. Solar Pro calculates total solar radiation using geographic coordinates of the site and meteorological data from the databases: 1,600 Points (1,600 Points, Japan Weather Association, 2001), TMY3 (NREL), MONSOLA-11, METPV-11, Meteonorm Meteo Monthly (Meteotest), NSRDB Hourly (NREL), and SolarGIS TMY Hourly (SolarGIS, GeoModel Solar). In this research, monthly averages of daily solar irradiation are obtained from the 1,600 Points meteorological database and the POA radiation is calculated using the Hay transposition model [Japan Solar Energy Society, New Solar Energy Utilization Handbook, 2010] [3,4,7,20,33,45,50–52].

PV F-Chart is software for designing all types of PV systems, battery storage systems, solar systems with concentrators, and tracking PV systems. Besides, this program can perform detailed financial analysis for isolated-, central-, and off-grid systems. PV energy output is performed as a function of solar radiation. PV F-chart does not support shading analysis and does not consider meteorological data and other loss factors for PV energy output calculations. POA radiation calculations are based on an isotropic (Liu and Jordan) sky model, while weather data are integrated as TMY2 file. In this research, for weather and solar data, PV F-Chart used TMY2 data and an isotropic (Liu and Jordan) sky model for POA radiation calculation. Based on solar module efficiency and temperature, PV array area, and incident angle, PV F-chart calculates the PV array performance [3,4,7,33,45,51,53–56].

PolySun is a software for designing, performance analyzing, and optimizing all types of solar (PV and thermal) and geothermal systems, cogeneration units, heat pumps, and combined systems and allows several different types of systems (heat pump, solar thermal, and PV systems) mutually to be combined. PolySun also provides performance, shading, and economic analyses of the designed systems and has an extensive library of various system components with all specific parameters necessary to simulate systems operation. This tool can assess the application of various PV technologies (c-Si, thin-film, μc-Si, HIT, and Ribbon). The dynamic simulation algorithm allows calculating all the relevant output parameters of the desired system. Weather and solar data are acquired from Meteonorm database. PolySun allows several options for weather data downloading: *from* *location* (according to Meteonorm 7.2 and Meteonorm 6), "*Profile*," "*External monthly values,*" and "*Webservice.*" In this research, for the location 'Niš' chosen specifically from the map, PolySun used the weather data from Meteonorm "Webservice". These data are dynamic and modified according to the Meteonorm website. For POA radiation calculations, PolySun uses Perez model. PV system energy output is calculated based on irradiance, module temperature, and loss factors (soiling and degradation, module mismatch, inverter load, and module derating factors) using H.G. Beyer model [3,4,7,20,33,45,57–60].

SAM is a software for different RES systems energy evaluation and financial assessments but cannot model hybrid systems. This software performs Parametric Analysis, Sensitivity Analysis, Statistical Analysis, and Probability of Exceedance Analysis. SAM has extensive libraries of RES systems' components along with all their coefficients and specifications data such as type of solar modules and inverters, collectors and parabolic receivers, wind turbines, *etc*. SAM provides detailed performance and financial analysis of all types of utility-interactive PV systems. SAM can assess the application of various PV technologies that include c-Si, thin-film, HIT, concentration photovoltaics (CPV), and multi-junction CPV. PV array performance calculations are based on the following models: empirical (Sandia), semi-empirical (five-parameter performance), Simple-efficiency, and PVWatts; while for the inverter performance calculations are based on Sandia inverter performance model and Single-point efficiency model. TRNSYS code is implemented in the PV array performance models. For solar resources and weather conditions in the USA, SAM uses data from the NREL Solar Prospector. For other locations, this tool can load data from the following files: TMY2, EnergyPlus weather, PVGIS, METEONORM, and TMY3. POA radiation calculations in SAM are based on isotropic and/or anisotropic sky models such as Liu and Jordan, Hay and Davies, Reindl and Perez models. Considering that 'Niš' is not covered by the NSRDB and Solar Resource Library, included in SAM, in this research, the solar data were imported from PVGIS-SARAH and Perez model is used as default transposition model for POA radiation calculations [2–4,7,20,22,33,42,45,48,51,61–66].

HOMER is a simulation tool for micro-grid and hybrid RES systems design. Besides technical and financial analysis, HOMER also provides system optimization, sensitivity analysis, and GHG analysis. HOMER imports solar data from NREL and NASA databases or users can import data manually. POA radiation calculations are based on the HDKR model. In this research, Homer used NASA database for monthly averages of global horizontal radiation from 1983 to 2005. The correlation of Erbs (1982) is used to calculate diffuse fraction, and the HDKR model is used for POA radiation calculations. PV power output is estimated based on incident solar radiation and PV cell temperature, but shading effects are not included in these calculations. Two versions of HOMER are available: HOMER Grid and HOMER Pro. HOMER Pro was designed for modeling distributed generation, and it focuses on the multi-generator islands or microgrids. HOMER Grid, used in this work, was designed for modeling behind-the-meter distributed energy systems [2–4,7,20,21,24,27,33,45,51,67–72].

As each PV tool contains internal submodels to estimate PV systems performance, the comparative overview of the main submodels integrated into described PV tools is given in Table 1.

3 Experiment

For the experimental examination of PV system operation, a fixed utility-interactive PV system of 2 kW_p (Figure 1) was set up at the Faculty of Sciences and Mathematics in Niš. Ten c-Si solar panels are fixed on the roof with an inclination angle of 32° to the south and serially interconnected in a string. The solar panels are free from any shading effect. By suitable cables, the solar panels are linked to a DC PV junction box, thence to a single-phase inverter, then to an AC PV junction box, and a distribution grid [73,74].

Sensor unit Sunny SensorBox, placed with an inclination angle of 32° to the south on the facility roof, measures global solar radiation, outdoor temperature, and wind speed. Sunny WEBBox, used as central communication interface, performs PV system monitoring and data acquisition. WEBBox is interconnected to the inverter and SensorBox by Bluetooth. The PV system output parameters and meteorological parameters are provided by a WEBBox. This device continuously records onto every 5 min the solar data and PV system electrical parameters (current, voltage, output power, *etc*.) into the internal memory and by the FTP server [73,74]. Input parameters and specifications of the given PV system, which were used in PV simulations by chosen PV tools, are given in Table 2.

4 Methodology

Evaluation of the effectiveness and suitability of PV software based on experimental analysis of the existing PV system operation was performed in four phases:

Table 1: The comparative overview of the main submodels integrated into described PV tools

PV tool	Solar databases (period)	POA radiation model	PV module model	System type	Analysis type
PVGIS 5	PVGIS–SARAH (2005–2016)	Muneer	Variant of King's model	• Any type of on-grid PV (flat-roof, roof-integrated, ground-mounted PV, tracking PVs) and off-grid PV	– Energy analyses
PVWatts	SWERA	Perez	PVForm equations	• Any type of on-grid PV	– Energy analyses
SolarGIS	Meteosat (1994-)	Perez	Single-diode model	• Any type of on-grid PV (flat-roof, roof-integrated, ground-mounted PV, and tracking PVs)	– Energy analyses
RETScreen	NASA-SEE (1983–2005)	Simple isotropic model described in in ref. [2]	Model based on work by Evans	• RES • No hybrid systems	– Energy analyses – Financial analyses – GHG analyses
BlueSol 4	NASA-SEE (1983–2005)	Simple isotropic model described in in ref. [2]	N/A	• Any type of on-grid PV (flat-roof, roof-integrated, ground-mounted PV, and tracking PVs) • Off-grid PV	– Energy analyses – Financial analyses – optimization
PVsyst 6.8.6	Meteonorm 7.2 (1991–2009)	Perez	Shockley's single-diode model	• Any type of on-grid PV (flat-roof, roof-integrated, ground-mounted PV, tracking PVs), • Off grid PV	– Energy analyses – Financial analyses
HelioScope	TMY Meteonorm	Perez	Shockley's single-diode model	• All type of on-grid PV • Single-axis tracking PV	– Energy analyses
PV*SOL premium	Meteonorm 7.1 (1991–2010)	Hay and Davies anisotropic model	Enhanced single-diode model	• On-grid PV • Off-grid PV • Tracking PVs	– Energy analyses – Financial analyses
Solarius PV	Meteonorm 7.1 (1991–2010)	N/A	N/A	• Any type of on-grid PV	– Energy analyses – Financial analyses – GHG analyses
Solar Pro 4.6	1,600 points	Hay transposition model	Single-diode model	• Any type of on-grid PV (flat-roof, roof-integrated, ground-mounted PV, and tracking PVs)	– Energy analyses – Financial analyses
PV F-Chart	TMY2	Liu and Jordan	Model based on work by Evans	• All types of PV systems • Battery storage systems • Solar systems with concentrators • Tracking PVs	– Energy analyses – Financial analyses – GHG analyses
PolySun	Meteonorm web	Perez	H.G. Bayer model	• All types of solar (PV and thermal) and geothermal systems • Cogeneration units • Heat pumps • Combined systems	– Energy analyses –Optimization

(*Continued*)

Table 1: *Continued*

PV tool	Solar databases (period)	POA radiation model	PV module model	System type	Analysis type
SAM	PVGIS-SARAH	Perez	Single-diode model	• RES • No hybrid systems	– Energy analyses – Financial analyses
Homer Grid	NASA-SEE (1983–2005)	HDKR	Equations described in ref. [2]	• Micro-grid • RES • Hybrid systems	– Energy analyses – Optimization – Sensitivity analysis – Financial analyses – GHG analyses

* The first two columns in Table 1 refer to the selected submodels in the applied simulations.

1) acquisition and statistical processing of experimental data,
2) running the chosen PV tools, based on the specified location, capacity, configuration, and characteristic PV system elements; while using these PV tools, the shadowing effects were not taken into account,
3) statistical processing of simulation results, and
4) comparing experimental and simulated results (solar irradiation and PV electricity generation).

Therefore, it was necessary to research the solar resources and PV tools, assay the selected PV tools, and conclude the PV software's applicability.

5 Results and discussion

The simulation results obtained by 14 described PV tools and results of experimental values of solar irradiation on an optimally inclined and south-oriented plane, as well as, amount of PV electricity produced by 2 kWp fixed utility-interactive PV system with c-Si solar panels oriented to the south at an optimal angle of 32°, in 2019 in Niš, are given and compared in this section. Besides, the PV system performance parameters, described in ref. [75] are also given, compared, and discussed in this section. The physical characteristics of all the system components, taken from the factory specifications data of the given components (Table 2), were used as input data in all the mentioned simulations.

5.1 Solar irradiation in Niš

As the solar irradiation reaching the array's surface impacts on PV array power output, PV tools use different methods for calculating the sum of incident solar irradiation on the PV array (POA irradiation). Some of them use ground and/or satellite measurements, and some use analytical models data. In this section, the simulation results, obtained by described PV tools and the experimental measurement results of the monthly average daily global solar irradiation on south-oriented and optimally inclined surface (32°) in Niš (POA irradiation in Niš), in 2019, are shown in Figure 2. The relative deviations of the monthly average daily POA irradiation in Niš obtained by simulations compared to experimental measurements in 2019 are shown in Figure 3.

Experimentally measured values of solar irradiation on the optimally inclined surface (32°) in Niš in 2019 are

Figure 1: Installed PV system of 2 kW_p in Niš.

Table 2: Input parameters and specifications of the given PV system

Geographical location	Latitude: 43°19′28.99″N, Longitude: 21°54′11.99″E, Niš, Serbia		
PV system			
Type	Grid-connected		
Nominal capacity	2 kW_p		
Mounting system	Fixed, rooftop		
Shading	No		
Solar module/type/power	Monocrystalline silicon/SST-200WM (*Shenzhen Sunco Solar Technology Co.*)/200 W		
Number of solar modules	10		
Orientation/inclination/azimuth angle	South/32°/0°		
Surface	1.659 m^2/module		
Physical characteristics of the solar modules in STC			
Maximum power (P_{max})	200 W		
Open circuit voltage (V_{oc})	57.12 V		
Short circuit current (I_{sc})	4.65 A		
Optimum power voltage (V_{mp})	46.46 V		
Optimum operating current (I_{mp})	4.3 A		
Temperature coefficients of V_{oc}	−0.38%/°C		
Temperature coefficients of I_{sc}	0.04%/°C		
Temperature coefficients of V_{mp}	−0.38%/°C		
Temperature coefficients of I_{mp}	0.04%/°C		
Temperature coefficients of P_{max}	−0.47%/°C		
FF	70–76%		
Physical characteristics of the inverter			
Type	Sunny Boy 2000HF-30 (*SMA Solar Technology AG*)		
Max efficiency	963%	Topology	HF transformer
Max DC power (@ cos φ = 1)	2.1 kW	Operating temperature range	−25 to +60°C
Max input voltage	700 V	Number of independent MPP inputs/strings per MPP input	1/2
MPP voltage range/rated input voltage	175–560 V/530 V	Max apparent AC power	2,000 VA
Min input voltage/initial input voltage	175 V/220 V	Nominal AC voltage/range	220 V, 230 V, 240 V/ 180–280 V
Max input current/Max input current per string	12 A/12 A	AC power frequency/range	50 Hz, 60 Hz/−4.5 to +4.5 Hz
Rated power (@ 230 V, 50 Hz)	2,000 W	Rated power frequency/rated grid voltage	50 Hz/230 V
Max output current	11.4 A	Feed-in phases/connection phases	1/1
Power factor at rated power	1	Self-consumption (night)	1 W
Technical characteristics of the sensor			
Type	Sunny SensorBox 2000HF-30 (*SMA Solar Technology AG*)		
Mounting	Outside, fixed, rooftop, no shading		
Orientation/inclination/azimuth angle	South/32°/0°		
Measurement range	0–1,500 W/m^2		
Resolution	1 W/m^2		
Measurement accuracy	±8%		

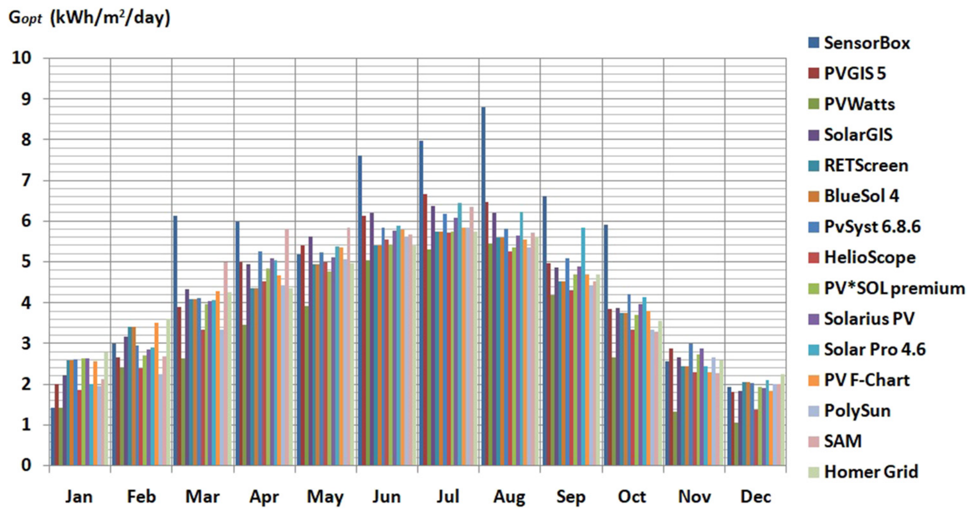

Figure 2: Monthly average daily POA irradiation (G_{opt}) in Niš.

obtained by SensorBox. Statistical processing and analysis of measurement show that the experimental monthly average daily solar irradiation on optimally inclined surface ranged between 1.42 (January) and 8.82 kW h/m^2/day (August).

The monthly average daily POA irradiation in Niš, obtained by ***PVGIS 5***, ranged between 1.82 (December) and 6.68 kW h/m^2/day (July). Comparison of the experimental and PVGIS SARAH solar data shows that the yearly average daily POA irradiation in Niš, obtained by PVGIS SARAH, is 18.07% lower than the experimental values obtained by the SensorBOX. The highest deviation of the PVGIS 5 simulation results in comparison with the experimental values is in January (42.3%), while the lowest deviation is in May (4.04%).

The monthly average daily POA irradiation in Niš, obtained by *PVWatts*, ranged between 1.07 kW h/m^2/day (December) and 5.47 kW h/m^2/day (July). Comparison of the experimental and PVWatts solar data shows that the yearly average daily POA irradiation in Niš, obtained by the PVWatts, is 38.38% lower than the experimental values, obtained by the SensorBOX. The highest deviation

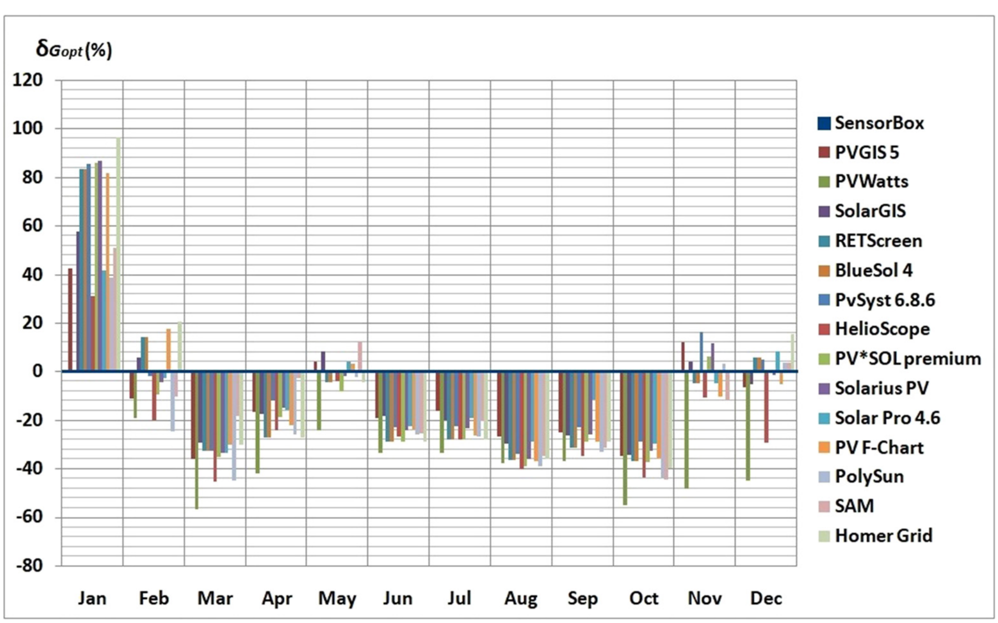

Figure 3: The relative deviations of monthly average daily POA irradiation (δ_{Gopt}) obtained by simulations compared to experimental measurements.

of the PVWatts simulation results in comparison with the experimental measurement values is in October (55.14%), while the lowest deviation is in January (0.7%).

The monthly average daily POA irradiation in Niš, obtained by ***SolarGIS***, ranged between 1.85 (December) and 6.39 kW h/m^2/day (July). Comparison of the experimental and SolarGIS solar data shows that the yearly average daily POA irradiation in Niš, obtained by the SolarGIS, is 17.13% lower than the experimental values, obtained by the SensorBOX. The highest deviation of the SolarGIS simulation results in comparison with the experimental measurement values is in January (57.75%), while the lowest deviation is in November (3.86%).

The monthly average daily POA irradiation in Niš, obtained by ***RETScreen***, ranged from 2.06 (December) to 5.75 kW h/m^2/day (July). Comparison of the experimental and RETScreen solar data shows that the yearly average daily POA irradiation in Niš, obtained by the RETScreen, is 22.51% lower than the experimental values, obtained by the SensorBOX. The highest deviation of the RETScreen simulation results in comparison with experimental measurement values is in January (83.1%), while the lowest deviation is in May (4.62%).

Considering that ***BlueSol 4*** uses the same solar database as RETScreen (NASA-SEE), the simulation results of monthly average daily POA irradiation in Niš obtained by BlueSol 4, as well as deviations, are the same as with RETScreen.

The monthly average daily POA irradiation in Niš, obtained by ***PVsyst 6.8.6***, ranged between 2.04 (December) and 6.19 kW h/m^2/day (July). Comparison of the experimental and PVsyst 6.8.6 solar data shows that the yearly average daily POA irradiation in Niš, obtained by the PVsyst 6.8.6., is 17.12% lower than the experimental values, obtained by the SensorBOX. The highest deviation of PVsyst simulation results in comparison with experimental measurement values is in January (85.21%), while the lowest deviation is in May (0.77%).

The monthly average daily POA irradiation in Niš, obtained by ***HelioScope***, ranged between 1.38 (December) and 5.74 kW h/m^2/day (July). Comparison of the experimental and HelioScope solar data shows that the yearly average daily POA irradiation in Niš, obtained by HelioScope, is 28.78% lower than the experimental values, obtained by the SensorBOX. The highest deviation of the HelioScope simulation results in comparison with the experimental measurement values is in March (45.51%), while the lowest deviation is in May (3.85%).

The monthly average daily POA irradiation in Niš, obtained by ***PV*SOL premium***, ranged between 1.94 (December) and 5.75 kW h/m^2/day (July). Comparison of the experimental and PV*SOL premium solar data shows that the yearly average daily POA irradiation in Niš, obtained by the PV*SOL premium, is 23.16% lower than the experimental values, obtained by the SensorBOX. The highest deviation of PV*SOL premium simulation results in comparison with the experimental measurement values is in January (85.92%), while the lowest deviation is in December (0.51%).

The monthly average daily POA irradiation in Niš, obtained by ***Solarius PV***, ranged from 1.92 (December) to 6.1 kW h/m^2/day (July). Comparison of the experimental and Solarius PV solar data shows that the yearly average daily POA irradiation in Niš, obtained by the Solarius PV, is 19.39% lower than the experimental values, obtained by the SensorBOX. The highest deviation of the Solarius PV simulation results in comparison with the experimental measurement values is in January (86.62%), while the lowest deviation is in December (1.54%).

The monthly average daily POA irradiation in Niš, obtained by ***Solar Pro 4.6***, ranged from 2.01 kW h/m^2/day (January) to 6.46 kW h/m^2/day (July). Comparison of the experimental and Solar Pro 4.6 solar data shows that the yearly average daily POA irradiation in Niš, obtained by the Solar Pro 4.6, is 16.82% lower than the experimental values, obtained by SensorBOX. The highest deviation of the Solar Pro 4.6 simulation results in comparison with the experimental measurement values is in January (41.55%), while the lowest deviation is in February (2.99%).

The monthly average daily POA irradiation in Niš, obtained by ***PV F-Chart***, ranged between 1.85 (December) and 5.86 kW h/m^2/day (July). Comparison of the experimental and PV F-Chart solar data shows that the yearly average daily POA irradiation in Niš, obtained by the PV F-Chart, is 20.39% lower than the experimental values, obtained by SensorBOX. The highest deviation of the PV F-Chart simulation results in comparison with the experimental measurement values is in January (81.69%), while the lowest deviation is in May (3.27%).

The monthly average daily POA irradiation in Niš, obtained by ***PolySun***, ranged between 1.97 (January) and 5.84 kW h/m^2/day (July). Comparison of the experimental and PolySun solar data shows that the yearly average daily POA irradiation in Niš, obtained by the PolySun, is 26.63% lower than the experimental values, obtained by SensorBOX. The highest deviation of the PolySun simulation results in comparison with the experimental measurement values is in January (38.73%), while the lowest deviation is in May (2.31%).

The monthly average daily POA irradiation in Niš, obtained by ***SAM***, ranged between 2.02 (December) and 6.36 kW h/m^2/day (July). Comparison of the experimental and SAM solar data shows that the yearly average daily POA irradiation in Niš, obtained by the SAM, is 18.75% lower than the experimental values, obtained by SensorBOX. The highest deviation of the SAM simulation results in comparison with the experimental measurement values is in January (50.7%), while the lowest deviation is in April (2.83%).

The monthly average daily POA irradiation in Niš, obtained by ***HOMER Grid***, ranged from 2.25 kW h/m^2/day (December) to 5.75 kW h/m^2/day (July). Comparison of the experimental and HOMER Grid solar data shows that the yearly average daily POA irradiation in Niš, obtained by the HOMER Grid, is 21.05% lower than the experimental values, obtained by SensorBOX. The highest deviation of HOMER Grid simulation results in comparison with the experimental measurement values is in January (96.48%), while the lowest deviation is in November (0.78%).

In all simulations, albedo is set uniformly at 0.2.

Based on statistical metrics, RMSE, rRMSE, and MAPA of POA irradiation range from 40.9 (Solar Pro) to 71.1 (PVWatts), 25.4 (Solar Pro) to 44.2 (PVWatts), and 18.6% (Solar Pro) to 36.2% (PVWatts), respectively. Therefore, only Solar Pro 4.6 gives good prediction (MAPA is between 10 and 20%), while all other simulation tools give reasonable predictions (20% < MAPA < 50%).

A comparative overview and analysis of the experimental and simulation solar data show that the highest deviations of the simulations in comparison with the experimental measurements of the monthly average daily POA irradiation in Niš in 2019 are in January, while the lowest deviations are in May. It can be concluded that the influence of clouds, water vapor, rain, fog, snow, aerosols, pollutants, dust, *etc.*, is not taken into account during the simulations in the winter months. The pollutant particles in the air during the heating (winter) season can significantly reduce direct solar radiation.

5.2 PV system electricity generation

Monthly values of electricity production from the 2 kW$_p$ fixed grid-connected PV system in Niš are discussed in this section. The simulation results, obtained by 14 selected PV tools, and the experimental measurement results of the monthly values of electricity production from the described PV system in Niš, in 2019, are presented in Figure 4.

Statistical processing and analysis of measurements show that in 2019 the monthly values of electricity generation from the PV system in Niš, obtained by WEBBox, range between 66.89 kW h (January) and 303.05 kW h (August), while simulation results range from:

- 94.5 kW h (December) to 305.8 kW h (July), obtained by PVGIS 5;
- 57 kW h (December) to 249 kW h (August), obtained by PVWatts;
- 98.77 kW h (December) to 294.35 kW h (July), obtained by SolarGIS;
- 107.78 kW h (December) to 270.703 kW h (July), obtained by RETScreen;
- 114.1 kW h (December) to 302.8 kW h (July), obtained by BlueSol 4;
- 109.7 kW h (December) to 296 kW h (July), obtained by PVsyst 6.8.6;
- 78.44 kW h (December) to 294.23 kW h (July), obtained by HelioScope;

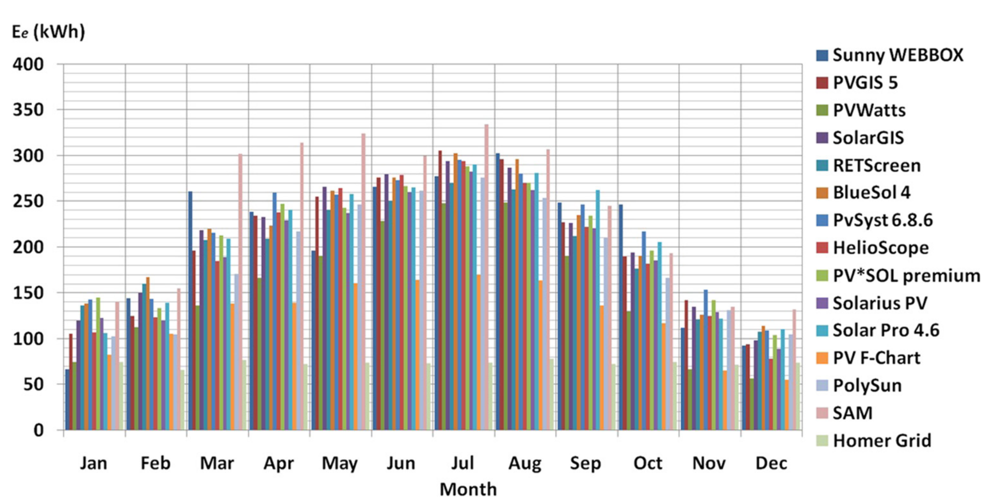

Figure 4: The experimental and simulation monthly values of PV system electricity generation.

- 104.53 kW h (December) to 288.4 kW h (July), obtained by PV*SOL premium;
- 89.28 kW h (December) to 282.72 kW h (July), obtained by Solarius PV;
- 106.73 kW h (January) to 290.93 kW h (July), obtained by Solar Pro 4.6;
- 55.5 kW h (December) to 170.6 kW h (July), obtained by PV F-Chart;
- 103 kW h (January) to 276 kW h/m^2 (July), obtained by PolySun;
- 132.245 kW h (December) to 334.761 kW h (July), obtained by SAM, and
- 72.05 kW h (November) to 78.7 kW h (August), obtained by HOMER Grid.

It should be noted that the experimental and simulation values of PV system electricity generation are values that the PV system, with a total surface of PV area of 16.59 m^2, transmits to the electricity distribution network. This parameter (surface of PV module area) is included in all simulations. If the norming of the PV electricity production per m^2 of the PV module area were performed, the presented values would be 16.59 times less than the ones shown and would be expressed in units of kW h/m^2.

In all simulations, PV system losses are chosen at 14%.

The relative deviations of monthly values of electricity generation from the 2 kW$_p$ fixed grid-connected PV system in Niš obtained by simulations compared to the experimental measurements in 2019 are shown in Figure 5.

An analysis of the experimental and simulation results shows that:

- the annual PV electricity production from the given system, obtained by the *PVGIS 5*, is 0.21% lower than the experimentally measured values, obtained by the WEBBox. The highest deviation of the PVGIS 5 simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in January (58.17%), while the lowest deviation is in December (1.78%).
- the annual PV electricity production from the given system obtained by *PVWatts* is 24.5% lower than the experimentally measured values, obtained by the WEBBox. The highest deviation of the PVWatts simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in October (47.34%), while the lowest deviation is in May (2.9%).
- the annual PV electricity production from the given system obtained by *SolarGIS* is 2.02% higher than the experimentally measured values, obtained by the WEBBox. The highest deviation of the SolarGIS simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in January (79.13%), while the lowest deviation is in April (2.32%).
- the annual PV electricity production from the given system obtained by the *RETScreen Expert* is 4.004% lower than the experimentally measured values, obtained by the WEBBox. The highest deviation of the RETScreen

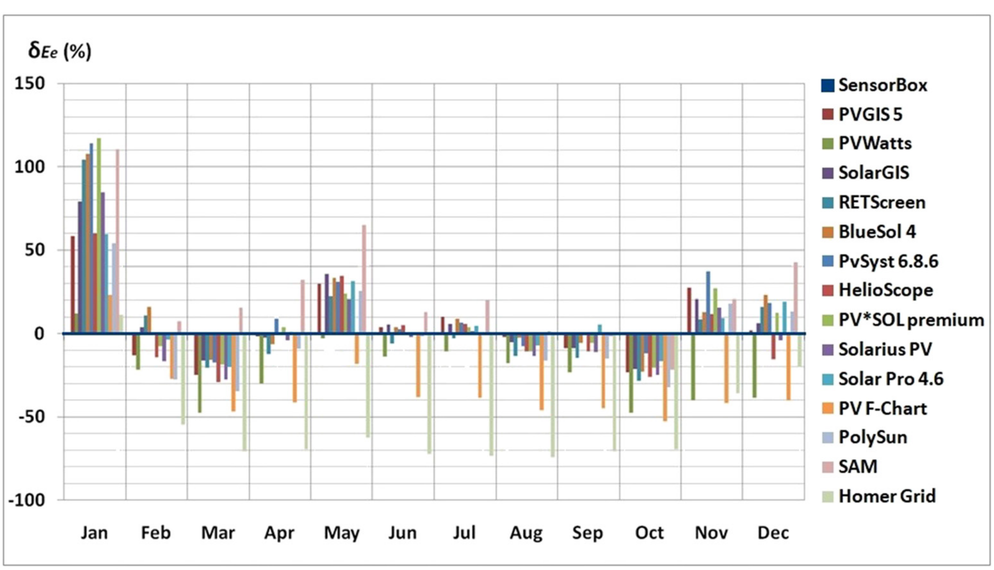

Figure 5: The relative deviations of monthly values of PV system electricity production (δ_{Ee}) obtained by simulations compared to experimental measurements.

simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in January (104.04%), while the lowest deviation is in July (2.64%).

- the annual PV electricity production from the given system obtained by *BlueSol 4* is 3.98% higher than the experimentally measured values, obtained by the WEBBox. The highest deviation of the BlueSol 4 simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in January (107.51%), while the lowest deviation is in August (2.26%).
- the annual PV electricity production from the given system obtained by *PVsyst 6.8.6* is 5.76% higher than the experimentally measured values, obtained by the WEBBox. The highest deviation of the PVsyst 6.8.6 simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in January (113.96%), while the lowest deviation is in February (0.44%).
- the annual PV electricity production from the given system obtained by *HelioScope* is 3.46% lower than the experimentally measured values, obtained by the WEBBox. The highest deviation of the HelioScope simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in January (59.89%), while the lowest deviation is in April (0.03%).
- the annual PV electricity production from the given system obtained by *PV*SOL premium* is 1.26% higher than the experimentally measured values, obtained by the WEBBox. The highest deviation of the PV*SOL premium simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in January (117.24%), while the lowest deviation is in June (0.32%).
- the annual PV electricity production from the given system obtained by *Solarius PV* is 5.12% lower than the experimentally measured values, obtained by the WEBBox. The highest deviation of the Solarius PV simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in January (84.45%), while the lowest deviation is in June (2.07%).
- the annual PV electricity production from the given system obtained by *Solar PRO 4.6* is 1.55% higher than the experimentally measured values, obtained by the WEBBox. The highest deviation of the Solar PRO 4.6 simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in January (59.56%), while the lowest deviation is in June (0.27%).
- the annual PV electricity production from the given system obtained by *PV F-Chart* is 38.8% lower than the experimentally measured values, obtained by the WEBBox. The highest deviation of the PV F-Chart simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in October (52.49%), while the lowest deviation is in May (18.05%).
- the annual PV electricity production from the given system obtained by *PolySun* is 8.4% lower than the experimentally measured values, obtained by the WEBBox. The highest deviation of the PolySun simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in January (53.98%), while the lowest deviation is in July (0.74%).
- the annual PV electricity production from the given system obtained by *SAM* is 17.49% higher than the experimentally measured values, obtained by the WEBBox. The highest deviation of the SAM simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in January (110.59%), while the lowest deviation is in August (1.34%).
- the annual PV electricity production from the given system obtained by *HOMER Grid* is 63.97% lower than the experimentally measured values, obtained by the WEBBox. The highest deviation of the HOMER Grid simulation results compared to the experimental measurement results of the monthly PV electricity production from the given system is in August (74.03%), while the lowest deviation is in January (11.44%).

The highest deviations of the simulation results compared to the experimental measurement results of the monthly energy production are in January, while the lowest deviations are in July and December (Figure 5). Figures 2 and 4 show that the simulation and measurement results follow the same trend over the year, with some exceptions. The most noticeable exception is the drop in experimentally measured solar radiation and energy production values in May. On the other hand, unexpectedly low energy production values over the year are obtained by HOMER Grid. Besides, the monthly production curve obtained by HOMER Grid is almost flattened (the difference between the minimum and maximum values is only 6.65 kW h). In addition to that, PV F-Chart and PVWatts provide significantly lower energy

Table 3: A comparative overview of the measured and simulated results of yearly average daily POA irradiation and PV system power output, as well as the relative deviations of simulated-to-measured values in Niš

Data	Sunny SensorBOX	PVGIS 5	PVWatts	SolarGIS	RETScreen	BlueSol 4	PVsyst 6.8.6	HelioScope	PV*SOL premium	Solarius PV	Solar Pro 4.6	PV F-Chart	PolySun	SAM	HOMER Grid
Yearly average daily POA irradiation (kW h/m^2/day)	5.27	4.32	3.25	4.37	4.09	4.09	4.37	3.76	4.05	4.25	4.39	4.2	3.87	4.28	4.16
The relative deviations δ_{Gopt} (%)	0.00	−18.1	−38.4	−17.13	−22.51	−22.51	−17.12	−28.78	−23.16	−19.39	−16.82	−20.39	−26.63	−18.75	−21.05
Data	**Sunny WEBBOX**	**PVGIS 5**	**PVWatts**	**SolarGIS**	**RETScreen**	**BlueSol 4**	**PVsyst 6.8.6**	**HelioScope**	**PV*SOL premium**	**Solarius PV**	**Solar Pro 4.6**	**PV F-Chart**	**PolySun**	**SAM**	**HOMER Grid**
Annual amount of PV system power production (kW h)	2455.6	2450.5	1854	2505.2	2357.3	2553.4	2597	2370.77	2486.49	2329.98	2493.79	1502.8	2250	2885.12	884.86
The relative deviations δ_E (%)	0.00	−0.21	−24.5	2.02	−4.004	3.98	5.76	−3.46	1.26	−5.12	1.55	−38.8	−8.37	17.49	−63.97

production values over the year (with the exception in January), while SAM provides significantly higher values in comparison with the experimental measurements over the year.

A comparative overview of the measured and simulated results of yearly average daily POA irradiation and PV system power output, as well as the relative deviations of simulated-to-measured values in Niš is given in Table 3.

Table 3 shows that annually measured values of daily global solar irradiation are approximately 22.2% greater than simulated. Besides, the highest deviation that occurs with PVWatts is expected, considering that the PVWatts for the location "Niš" use the weather data from the nearest NREL international weather station (in this case it is (INTL) Sofia, Bulgaria).

However, the estimated values of PV energy production are relatively close to the experimentally measured value (approximately 8%), with the exception of the PV F-Chart, PVWatts, and HOMER. More significant deviations in PV energy production that occur with PV F-Chart, PVWatts, and HOMER are expected since PV F-Chart, PVWatts, and HOMER use the most basic data for PV electricity generation calculations, not taking into account variations caused by inverters, solar modules, and other electric variables. These tools do not support the advanced calculations and detailed inputs are needed. It is obvious that the discrepancy between experimental and simulation values for yearly average daily POA irradiation is significantly higher (about 22%) than the discrepancy for the annual amount of PV system power production (about 8%) for 2019. It is assumed that the simulations take into account higher electrical losses in the PV system than they actually are. However, the modeled POA irradiation combination being lower than experimentally measured, but simulated energy production approximately matching what was experimentally measured indicates that the PV tools will considerably overestimate PV system energy production if a typical or an average weather year were to appear and present. For a more adequate assessment of PV tools applications by comparative analysis of experimental and simulated quantities, it is necessary to use the average long-term (min 10-year) measurements of these parameters.

Based on statistical metrics, RMSE, rRMSE, and MAPA of PV system electricity production range from 35.5 (PVGIS 5) to 151.12 (HOMER Grid), 17.35 (PVGIS 5) to 73.85 (Homer Grid) and 17.1% (PVGIS) to 57.0% (HOMER Grid), respectively. Therefore, only PVGIS 5 gives good prediction for PV electricity production (MAPA is between 10 and 20%). All other simulation tools give reasonable predictions (20% < MAPA < 50%), except PV F-Chart (MAPA = 38.2%) and HOMER (MAPA = 57%).

5.3 Performance ratio (PR)

PR of PV system is the ratio between the specific yield factor Y_f and the reference yield factor Y_r, where *reference yield* Y_r is defined as the ratio between the total POA radiation and the reference radiation of 1 kW/m^2 and

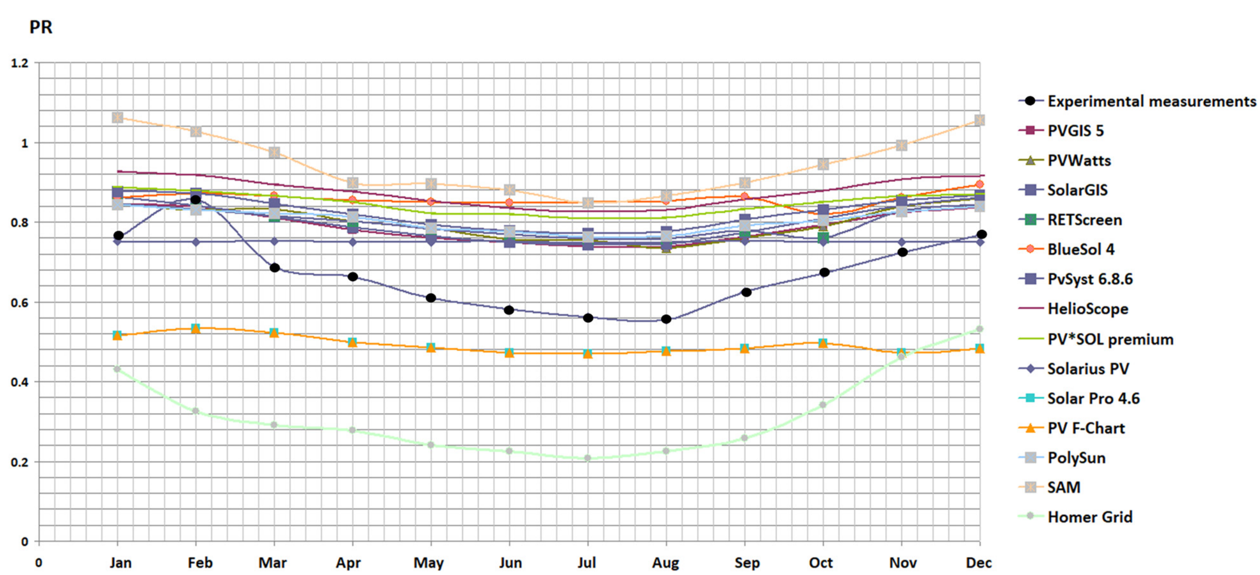

Figure 6: The experimental and simulation monthly values of PR.

specific yield factor Y_f (kW h/kW) is the ratio of the PV system electricity generated and the total PV system installed power. PV system PR is given by Eq. (1):

$$\mathrm{PR} = \frac{Y_f}{Y_r} = \frac{\dfrac{E_e(\mathrm{kW\,h})}{P_{\max}(\mathrm{kW})}}{\dfrac{G_{\mathrm{opt}}\ (\mathrm{kW\,h/m^2})}{1\ (\mathrm{kW/m^2})}}. \qquad (1)$$

The reference yield factor Y_r presents the solar irradiation resource for the PV system and is a function of the geographical location and PV array orientation, while the Y_f is a parameter used to normalize the energy produced with respect to the size of the PV system, and which is a good method of comparing the energy generated by differing sized PV systems. Therefore, the PR represents the rate of effective energy generated with the energy that the system would produce if it continuously operated on its STC efficiency. So, the PR includes all PV system losses (optical and electric losses), gives the correlation of the PV system quality between installations in different locations and PV array orientations and does not directly depend on input parameters like the meteo inputs, PV panel efficiency, and PV array orientation. In this research, the experimental and simulation monthly values of PR are given in Figure 6.

As PR is a quantitative characteristic of all losses in the PV system, due to losses that occur in summer due to the increase in PV module temperature, PR values are smaller in the summer than in the winter and, in the general case, are in the range between 0.6 and 0.8. The experimental monthly values of PR range from 0.55 (August) to 0.86 (February), as shown in Figure 6, while the annual mean experimental value of PR is 0.67. The annual mean values of PR, obtained by simulations, range from 0.32 (HOMER) to 0.95 (SAM).

Generally, the simulation and experimental measurement values of PR follow the same trend over the year, except in February, which in 2019 had higher temperatures and less precipitation and snow, which is unusual for that time of the year. Monthly values of PR obtained by simulations are higher than experimental, with some exceptions (HOMER Grid, PV F-Chart, and Solar Pro 4.6). This indicates that simulation values approach the ideal behavior of the given PV system. Annually, the highest deviation of the simulation results compared to the experimental results of the PR is obtained by HOMER Grid (52.2%), while the lowest deviation is obtained by PVGIS 5 (17.9%).

5.4 Capacity factor (CF)

CF of PV system is the ratio between the actual PV electricity generation and PV electricity generation if the PV system operates with its nominal (total installed) power 24 h throughout the year. PV system CF is given by Eq. (2):

$$\mathrm{CF} = \frac{Y_f\ (\mathrm{kW\,h/kW})}{8,760\ (\mathrm{h})}. \qquad (2)$$

CF depends on the PV system installation location and is directly proportional to the PV system's performance. In this research, the experimental and simulation monthly values of CF are given in Figure 7.

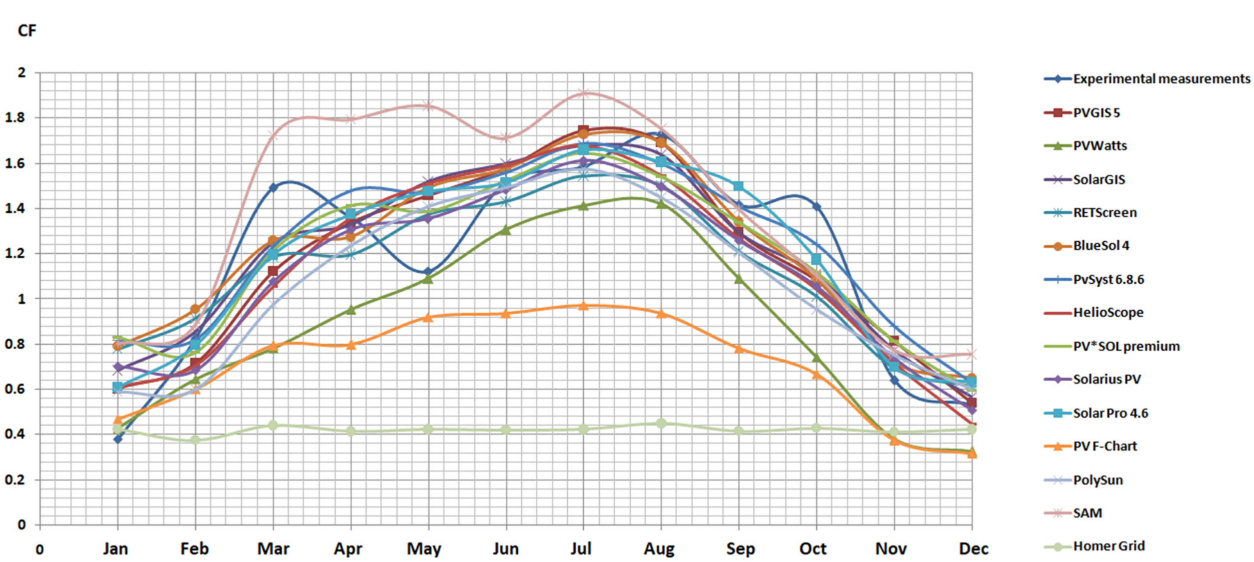

Figure 7: The experimental and simulation monthly values of CF.

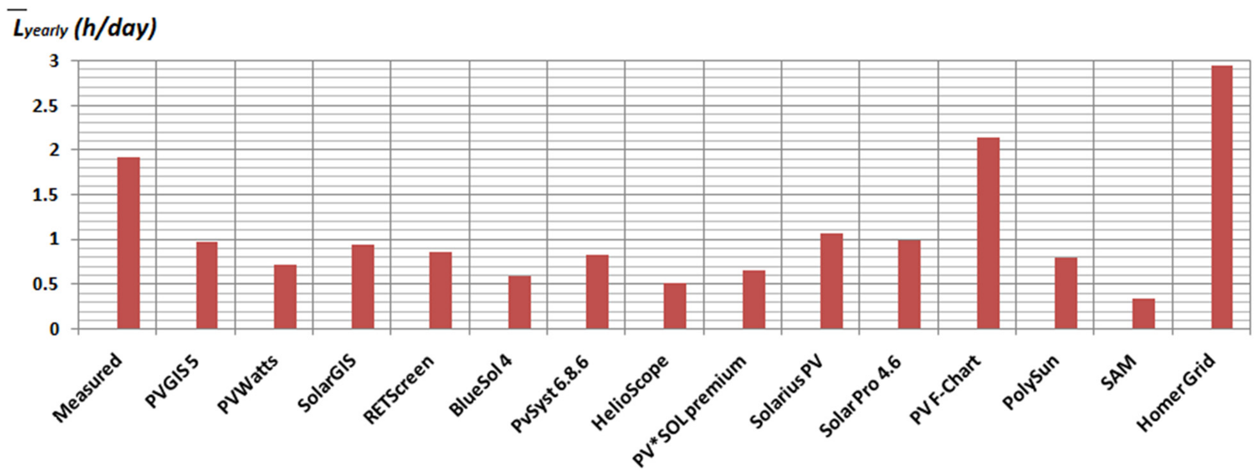

Figure 8: The annual mean values of total energy loss from the given PV system.

Figure 7 shows that CF values are higher in the summer than in the winter. The experimental monthly values of CF range from 0.39 (January) to 1.73 (August), while the annual mean experimental value of CF is 1.17. The annual mean values of CF, obtained by simulations, range from 0.42 (HOMER) to 1.37 (SAM). Generally, the simulation and experimental measurement values of CF follow the same trend over the year, except in May. Annually, the highest deviation of the simulation results compared to the experimental results of the CF is obtained by HOMER Grid (63.96%), while the lowest deviation is obtained by PVGIS 5 (0.2%).

5.5 Total energy losses

The difference between *reference yield* Y_r and *specific yield factor* Y_f represents the total energy loss (L) from the given PV system. The annual mean values of total energy loss from the given PV system are given in Figure 8.

The annual mean experimental value of total energy loss from the given PV system is 1.92 h/day, while the annual mean simulation values range between 0.34 h/day (SAM) and 2.95 h/day (HOMER). Besides, the highest deviation of the simulation results compared to experimental of the annual mean value of total energy loss from the given PV system is obtained by HOMER Grid (53.7%).

The PV system size used in this study is small and cannot reflect the real losses associated with the Megawatt level of the plant. However, based on testing PV tools for PV systems operation prediction and comparing simulation and experimental data for small PV systems, a similar assessment and choice of the most suitable PV tools for large-scale PV system operation prediction could be the same for the same climatic regions.

6 Conclusion

This research includes testing and evaluation of 14 PV tools. The same initial items and conditions in each simulation have been determined based on an experimental study in Niš. An evaluation and comparative analysis between each PV software, as well as their deviations from the experimental measurements in Niš, in 2019, indicate that:

- The yearly average daily POA irradiation, obtained by SensorBox, is 5.27 kW h/m^2/day.
- All solar datasets, implemented in the mentioned PV tools, give lower amounts of the yearly average value of daily POA irradiation.
- Annually, the highest deviation of the simulation results compared to the experimental measurements of the average daily POA irradiation is obtained by PVWatts (38.38%), while the lowest deviations are obtained by Solar Pro 4.6 (16.82%) and PVsyst 6.8.6. (17.12%).
- Monthly, the highest deviations of the simulation results compared to the experimental measurements of the monthly average daily POA irradiation are in January. It is explained by the fact that the influence of clouds, water vapor, rain, fog, snow, aerosols, pollutants, dust, *etc.*, is not taken into account during the simulations in the winter months. On the other hand, the lowest deviations of the simulation results compared to the experimental measurements of the monthly average daily POA irradiation are in May. It is evident that the impact of pollutant particles in the air during the heating (winter) season, rain, snow, *etc.*, is not present during the spring and summer months, so the good agreement between experimental and simulation data in those months is obtained. It should also be noted that solar databases, implemented in described PV tools, represent the averages

of long-term measurements, while the current research presents measured values for 1 year (2019). Therefore, in this case, the lowest deviations are in May, but it would probably change depending on which measurement year was used (but it would certainly be the summer or spring months).
- The total annual PV electricity production from the given system, obtained by WEBBox, is 2455.621 kW h.
- Annually, the highest deviation of the simulation results compared to the experimental measurements of the total PV electricity production from the given system is obtained by HOMER Grid (63.97%), while the lowest deviation is obtained by PVGIS 5 (0.21%).
- Annual mean experimental values of PR and CF were 0.67 and 1.17, respectively.
- PVGIS 5 gives the most approximate annual value of the given PV system's power output and other performance parameters compared with the experimental measurements. It probably stems from the fact that PVGIS 5 provides the average monthly electricity production values for each year starting from 2005 to 2016 with a yearly average standard deviation of approximately 29.62%.

It is indisputable that the selection of solar datasets significantly influences PV power production. However, it is also evident that PV power production depends not only on solar irradiation but also on various factors such as weather conditions, soiling, system losses, *etc*. The differences between the measured and simulated results of the PV power production to a large extent are due to the assessed PV system losses. Besides, PV power production would probably modify depending on which measurement year was used.

To the results presented in this article, to predict the PV systems operations, simulation tools specifically created for PV applications give more accurate forecasts and are closer to experimental data than those that include additional RES and hybrid systems. If the climatic characteristics of Serbia and regions with similar climatic conditions are taken into account, PVGIS 5 simulation gives the most accurate data compared to the experimental data for PV power production. On the other hand, PV tools that use SARAH or Meteonorm solar databases and the Perez model for POA radiation calculations give closer values to the experimental values than those that use NASA solar database and simple isotropic sky model.

Considering that meteorological parameters have the significant impact on the PV systems operations, the results in this work are relevant for the given location and the sites with similar climatic conditions, and it cannot be stated that deviations of simulation results from experimental results will be the same for other locations worldwide as well as the applicability of PV tools. Thus, this research provides substantial information on the most commonly used PV tools and contributes beneficial insights into the experimental and simulation results of PV system operation for specific climate areas.

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References

[1] Wilson GM, Al-Jassim M, Metzger WK, Glunz SW, Verlinden P, Xiong G, et al. The 2020 photovoltaic technologies roadmap. J Phys D: Appl Phys. 2020;53(493001):1–47.
[2] Duffie JA, William ABeckman. Solar engineering of thermal processes. 4th edn. Hoboken, New Jersey: John Wiley & Sons, Inc; April 2013. p. 944. ISBN: 978-0-470-87366-3.
[3] Klise GT, Stein JS. Models used to assess the performance of photovoltaic systems, Sandia report, SAND2009-8258;

December 2009. p. 61. doi: 10.2172/974415. https://www.osti.gov/biblio/974415-models-used-assess-performance-photovoltaic-systems.
[4] Lalwani M, Kothari DP, Singh M. Investigation of solar photovoltaic simulation softwares. Int J Appl Eng Res Dindigul. 2010;1(3):585–601.
[5] Pavlović T, Milosavljević D, Radonjić I, Pantić L, Radivojević A, Pavlović M. Possibility of electricity generation using PV solar plants in Serbia. Renew Sust Energ Rev. 2013;20:201–18.
[6] https://www.pravno-informacioni-sistem.rs/SlGlasnikPortal/eli/rep/sgrs/skupstina/ostalo/2015/101/1/r.
[7] Umar N, Bora B, Banerjee C, Panwar BS. Comparison of different PV power simulation software: case study on performance analysis of 1 MW grid-connected PV solar power plant. Int J Eng Sci Invent (IJESI). 2018;7(7-Ver II):11–24.
[8] Krystian C, Piotr D. Comparison of the existing photovoltaic power plant performance simulation in terms of different sources of meteorological data. E3S Web of Conferences 49, SOLINA 2018, 00015; 2018. p. 1–8. doi: 10.1051/e3sconf/20184900015.
[9] https://ec.europa.eu/jrc/en/PVGIS/docs/methods.
[10] Gracia Amillo AM, Huld T. Performance comparison of different models for the estimation of global irradiance on inclined surfaces. Validation of the model implemented in PVGIS. JRC Technical Report EUR 26075 EN, JRC81902; April 2013. p. 26. ISBN 978-92-79-32507-6, ISSN 1831-9424 doi: 10.2790/915542013.
[11] Guerrero-Lemusa R, Cañadillas-Ramalloa D, Reindl T, Valle-Feijóoc JM. A simple big data methodology and analysis of the specific yield of all PV power plants in a power system over a long time period. Renew Sust Energ Rev. 2019;107:123–32.
[12] Urraca R, Martinez-de-Pison E, Sanz-Garcia A, Antonanzas J, Antonanzas-Torres F. Estimation methods for global solar radiation: Case study evaluation of five different approaches in central Spain. Renew Sust Energ Rev. 2017;77:1098–113.
[13] Psomopoulos CS, Ioannidis GCH, Kaminaris SD, Mardikis KD, Katsikas NG. A comparative evaluation of photovoltaic electricity production assessment software (PVGIS, PVWatts and RETScreen). Environ Process. 2015;2(1):S175–89.
[14] Kesler S, Kivrak S, Dincer F, Rustemli S, Karaaslan M, Unal E, et al. The analysis of PV power potential and system installation in Manavgat, Turkey – A case study in winter season. Renew Sust Energ Rev. 2014;31:671–80.
[15] https://solargis.com/docs/methodology.
[16] Shukla AK, Sudhakar K, Baredar P. Simulation and performance analysis of 110kWp grid-connected photovoltaic system for residential building in India: A comparative analysis of various PV technology. Energy Rep. 2016;2:82–8.
[17] Danandeh MA, Mousavi GSM. Solar irradiance estimation models and optimum tilt angle approaches: A comparative study. Renew Sust Energ Rev. 2018;92:319–30.
[18] Makarova A. Study, design and performance analysis of a grid-connected photovoltaic system case study: 5 MW grid-connected PV System in Namibia. Bachelor's Thesis. Metropolia, Finland: Helsinki Metropolia University of Applied Sciences; 14 November 2017. p. 61.
[19] https://pvwatts.nrel.gov/.
[20] Rozmi MDAB, et al. Role of immersive visualization tools in renewable energy system development. Renew Sust Energ Rev. 2019;115:109–363.
[21] Tozzi Jr P, Jo JH. A comparative analysis of renewable energy simulation tools: Performance simulation model vs system optimization. Renew Sust Energ Rev. 2017;80:390–8.
[22] Jakica N, et al. BIPV Design and Performance Modelling: Tools and Methods. IEA PVPS Task 15, Subtask E – Demonstration. Draft Report IEA-PVPS T15-09: 2019. IEA International Energy Agency, Photovoltaic Power Systems Programme; 2019. p. 83. ISBN: 978-3-906042-86-2.
[23] Roberts JJ, Zevallos AAM, Cassula AM. Assessment of photovoltaic performance models for system simulation. Renew Sust Energ Rev. 2017;72:1104–23.
[24] Sinha S, Chandel SS. Review of software tools for hybrid renewable energy systems. Renew Sust Energ Rev. 2014;32:192–205.
[25] Lee K-H, Lee D-W, Baek N-C, Kwon H-M, Lee C-J. Preliminary determination of optimal size for renewable energy resources in buildings using RETScreen. Energy. 2012;47(1):83–96.
[26] https://power.larc.nasa.gov/.
[27] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy. 2010;87(4):1059–82.
[28] Rashwan SS, Shaaban AM, Al-Suliman F. A comparative study of a small-scale solar PV power plant in Saudi Arabia. Renew Sust Energ Rev. 2017;80:313–8.
[29] Bustos F, Toledo A, Contreras J, Fuentes A. Sensitivity analysis of a photovoltaic solar plant in Chile. Renew Energy. 2016;87:145–53.
[30] http://www.bluesolpv.com/dnnsite/Products/Documentation.aspx.
[31] Kut P, Nowak K. Design of photovoltaic systems using computer software. JEcolEng. 2019;20(10):72–8.
[32] https://www.pvsyst.com/.
[33] Sharma DK, Verma V, Singh AP. Review and analysis of solar photovoltaic software. Int J Curr Eng Technol. 2014;4(2):725–31.
[34] Vuuren DJ, Marnewick A, Pretorius JHC. A proposed simulation-based theoretical preconstruction process: The case of solar photovoltaic technology in South African shopping centres. Renew Sust Energ Rev. 2019;113:109–295.
[35] Omar MA, Mahmoud MM. Grid connected PV-home systems in Palestine: A review on technical performance, effects and economic feasibility. Renew Sust Energ Rev. 2018;82:2490–7.
[36] Mahachi T. Energy yield analysis and evaluation of solar irradiance models for a utility scale solar PV plant in South Africa. Master's Thesis. Stellenbosch, South Africa: Faculty of Engineering at Stellenbosch University; 2016. p. 214.
[37] Okello D, van Dyk EE, Vorster FJ. Analysis of measured and simulated performance data of a 3.2 kWp grid-connected PV system in Port Elizabeth. South Afr Energy Convers Manag. 2015;100:10–5.
[38] Barua S, Prasath RA, Boruah D. Rooftop solar photovoltaic system design and assessment for the academic campus using PVsyst software. Int J Electron Electr Eng. 2017;5(1):76–83.

[39] Petrović I, Šimić Z, Vražić M. Comparison of PV plant energy generation prediction tools with measured data. Prz Elektrotechnzny. 2013;89(6):121–4.
[40] https://www.folsomlabs.com/modeling.
[41] Ali MS, Rima NN, Sakib MIH, Khan MF. Helioscope based design of a MWP solar PV plant on a marshy land of Bangladesh and prediction of plant performance with the variation in tilt angle. GUB J Sci Eng. 2018;5(1):1–5.
[42] Guittet DL, Freeman JM. Validation of photovoltaic modeling tool helioscope against measured data. Golden, CO: National Renewable Energy Laboratory, NREL/TP-6A20-72155; November 2018. p. 13. https://www.nrel.gov/docs/fy19osti/72155.pdf.
[43] https://valentin-software.com/en/products/pvsol-premium/.
[44] Hofmann M, Seckmeyer G. A new model for estimating the diffuse fraction of solar irradiance for photovoltaic system simulations. Energies. 2017;10(2):248. doi: 10.3390/en10020248.
[45] Jakica N. State-of-the-art review of solar design tools and methods for assessing daylighting and solar potential for building-integrated photovoltaics. Renew Sust Energ Rev. 2018;81(1):1296–328.
[46] Axaopoulos PJ, Fylladitakis ED, Gkarakis K. Accuracy analysis of software for the estimation and planning of photovoltaic installations. Int J Energy Env Eng. 2014;5(1):1–7.
[47] https://www.acca.it/software-fotovoltaico.
[48] Diaconu A, Crăciunescu D, Fara L, Sterian P, Oprea C, Fara S. Estimation of electricity production for a photovoltaic park using specialized advanced software. Proceedings Paper. EuroSun 2016; Published by International Solar Energy Society Selection; October 2016. p. 9. doi: 10.18086/eurosun.2016.08.18.
[49] Alktranee MHR, Al-Yasiri Q, Sahib MM. Power output enhancement of grid-connected PV system using dual-axis tracking. Renew Energy Environ Sustain. 2020;5(8):1–7.
[50] https://www.lapsys.co.jp/english/products/pro.html.
[51] Alsadi S, Khatib T. Photovoltaic power systems optimization research status: A review of criteria, constrains, models, techniques, and software tools. Appl Sci. 2018;8(1761):1–30. doi: 10.3390/app8101761.
[52] Perez-Gallardo JR, Azzaro-Pantel C, Astier S, Domenech S, Aguilar-Lasserre A. Ecodesign of photovoltaic grid-connected systems. Renew Energy. 2014;64:82–97.
[53] http://fchartsoftware.com/pvfchart/.
[54] https://core.ac.uk/download/pdf/18599564.pdf.
[55] Juan CM, Baltazar C, Haberl J. Comparison between TRNSYS software simulation and PV F-chart program on photovoltaic system. Energy Systems Laboratory (http://esl.tamu.edu). Texas A&M University (http://www.tamu.edu), ESL-TR-12-04-02; April 2012. p. 15.
[56] Haberl JS, Cho S. Literature review of uncertainty of analysis methods (PV F-Chart Program). Report to the Texas commission on environmental quality. Energy Systems Laboratory. Texas A&M University. ESL-TR-04/10-02; October 2004. p. 17. (http://esl.tamu.edu).
[57] https://www.velasolaris.com/?lang=en.
[58] https://www.velasolaris.com/wp-content/uploads/2019/02/Tutorial_EN.pdf.
[59] Kalogirou SA. Energy engineering: processes and systems. 2nd edn. Boston, USA: Academic Press; 2014. p. 840. ISBN 978-0-12-397270-5, Copyright © 2014 Elsevier Inc.
[60] Ogbonnaya C, Turan A, Abeykoon C. Robust code-based modeling approach for advanced photovoltaics of the future. Sol Energy. 2020;199:521–9.
[61] https://sam.nrel.gov/.
[62] Blair N, Dobos AP, Freeman J, Neises T, Wagner M. System advisor model, SAM 2014.1.14: General DESCRIPTION. National Renewable Energy Laboratory; February 2014. p. 13. https://www.nrel.gov/docs/fy14osti/61019.pdf.
[63] Sengupta M, Habte A, Gueymard C, Wilbert S, Renné D, Stoffel T, editors. Best practices handbook for the collection and use of solar resource data for solar energy applications. 2nd edn. National Renewable Energy Laboratory; December 2017. p. 238. https://www.nrel.gov/docs/fy18osti/68886.pdf.
[64] Gilman P, Dobos A, DiOrio N, Freeman J, Janzou S, Ryberg D. SAM Photovoltaic model technical reference update. National Renewable Energy Laboratory; March 2018. p. 89. https://www.nrel.gov/docs/fy18osti/67399.pdf.
[65] Martín-Pomaresa L, Martínez D, Polo J, Perez-Astudillo D, Bachour D, Sanfilippo A. Analysis of the long-term solar potential for electricity generation in Qatar. Renew Sust Energ Rev. 2017;73:1231–46.
[66] Navabi R, Abedi S, Hosseinian SH, Pal R. On the fast convergence modeling and accurate calculation of PV output energy for operation and planning studies. Energy Convers Manag. 2015;89:497–506.
[67] https://www.homerenergy.com/.
[68] Groissböck M. Are open source energy system optimization tools mature enough for serious use? Renew Sust Energ Rev. 2019;102:234–48.
[69] Pavlović T, Milosavljević D, Piršl D. Simulation of PV systems electricity generation using Homer software in specific locations in Serbia. Therm Sci. 2013;17(2):333–47.
[70] Bahramara S, Moghaddam MP, Haghifam MR. Optimal planning of hybrid renewable energy systems using HOMER: A review. Renew Sust Energ Rev. 2016;62:609–20.
[71] Cuesta MA, Castillo-Calzadilla T, Borges CE. A critical analysis on hybrid renewable energy modeling tools: An emerging opportunity to include social indicators to optimise systems in small communities. Renew Sust Energ Rev. 2020;122:109691.
[72] Anoune K, Bouya M, Astito A, Abdellah AB. Sizing methods and optimization techniques for PV-wind based hybrid renewable energy system: A review. Renew Sust Energ Rev. 2018;93:652–73.
[73] Milosavljević DD, Pavlović TM, Piršl DS. Performance analysis of a grid-connected solar PV plant in Niš. Repub Serb Renew Sust Energ Rev. 2015;44:423–35.
[74] Milosavljević D. Influence of meteorological parameters on the operation of a grid – connected PV solar plant. Univ Thought Publ Nat Sci. 2018;8(1):56–61.
[75] Iftikhar H, Sarquis E, Branco PJC. Why can simple operation and maintenance (O&M) practices in large-scale grid-connected PV power plants play a key role in improving its energy output? Energies. 2021;14(13):3798.