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INVESTIGATION OF THE ENERGY EFFICIENCY OF PV SOLAR POWER PLANT INSTALLED AT THE FACULTY OF SCIENCES AND MATHEMATICS, UNIVERSITY OF NIŠ†

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Abstract. *The paper provides basic information on the 2 kWp PV solar power plant with monocrystalline silicon solar modules installed on the roof of the Faculty of Sciences and Mathematics (FSM), University of Niš, and the equipment for the investigation of its energy efficiency depending on the real climate conditions. Furthermore, results of the simulation and experimental determination of the energy efficiency of the PV solar power plant at FSM in Niš, in the period from July 1, 2013 to January 1, 2014, are given. It was found that in this time period the average values of the experimental and simulation calculated energy efficiencies of the PV solar power plant were 9.52% and 8.44%, respectively. The increase in the ambient temperature caused a decrease in the PV solar power plant energy efficiency; with an increase in ambient temperature by 1 °C, the experimental energy efficiency decreased by 0.22%, and the simulation calculated energy efficiency decreased by 0.07%. The obtained data could be used for the planning and application of PV solar power plants in places with a similar climate.*

Key words: *solar irradiation, PV solar plant, energy efficiency of PV solar power plant, PVGIS*

1. INTRODUCTION

A photovoltaic (PV) solar system denotes a system by which solar irradiation is converted into the electrical energy which is then distributed to the consumers as a single phase and/or alternating current electric power. PV solar system can run independently from the electric-distribution grid (off-grid PV system) or it can be connected to the grid (on-grid PV system). On-grid PV solar systems are composed of the solar modules, an

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inverter which converts variable direct current (DC) into the utility frequency alternating current (AC), a monitoring system, a transformer, used to transfer generated electrical energy onto the grid, and the connecting lines to connect PV solar system to the network grid. In these systems the total amount of the generated electrical energy is transferred to the networking grid (Parida et al., 2011; Solanski, 2013; Tiwari and Dubey, 2010). These systems comprise PV solar power plants of great power installed on earth, and PV solar power plants of small power, installed on the private houses, residential and other types of objects (Pavlovic et al., 2013a; Masters, 2004; Thornycroft and Markvart, 2003; Bojic and Blagojevic, 2006). This paper gives the simulation and experimental results of the energy efficiency of the 2 kWp PV solar power plant installed at the FSM in Niš, in the period from July 1, 2013 to January 1, 2014.

2. PV SOLAR POWER PLANT AT FSM, UNIVERSITY OF NIŠ

A PV solar power plant at FSM, University of Niš, consists of 10 serial connected monocrystalline silicon solar modules, single power of 200 Wp (*SST-200WM, Shenzhen Sunco Solar Technology Co*.); DC and AC frame rack, inverter and monitoring system which gives the information on the electrical parameters of the PV solar power plant (Milosavljevic et al., 2015; Pavlovic et al., 2013b). Schematics of solar modules connection in *string*, RO-DC connection and RO-AC connection in 2 kWp PV solar power plant installed on the roof of FSM in Niš, is given in Figure 1.

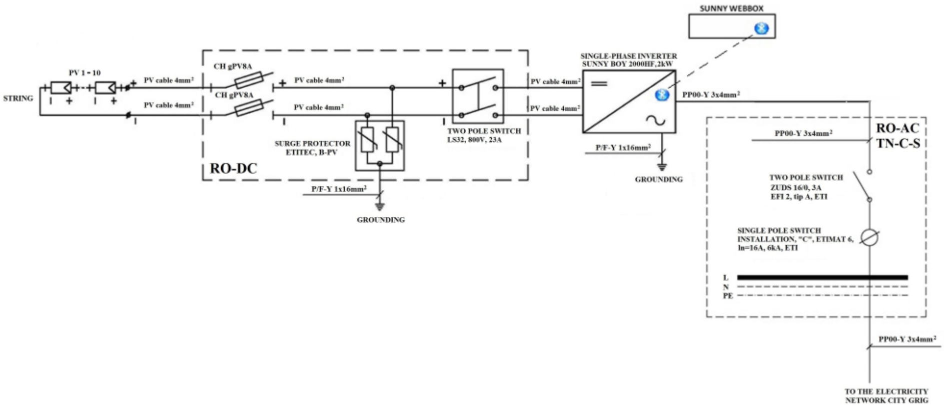

Fig. 1 Schematics of solar modules connection in string, RO-DC connection and RO-AC connection in 2 kWp PV solar power plant installed on the roof of FSM in Nis

Solar modules, with surface of 1.659 m^2/modul (total PV module area is 16.59 m^2), are based on the metal stainless steel foundation inclined at 32º towards the south. By the adequate conductors, solar modules are connected to a DC frame rack (RO-DC), a single phase inverter (*Sunny Boy 2000 HF-30*, power of 2 kW), an AC frame rack (RO-AC) and the city grid, as can be seen in Figure 1. The DC and AC frame racks contain protective components providing steady solar power plant functioning. At the output of the AC frame rack there is a single phase alternating voltage 230V, 50Hz. Data on the amount of the electrical energy generated by PV solar power plant are provided by WEBBOX, which by Bluetooth, is connected with the inverter (Milosavljevic et al., 2015; Pavlovic et al., 2013b). A 2 kWp PV solar power plant, installed at FSM in Niš, is given in Figure 2.

Fig. 2 A 2 kWp PV solar power plant installed at FSM in Niš

3. EXPERIMENT

3.1. Meteorological parameters measurement

In the period from July 1, 2013 until January 1, 2014 for the measurement of the solar irradiation falling on one square meter of the surface oriented southward, at the angle of 32° in relation to the horizontal surface, wind speed and the ambient temperature at FSM in Niš, a Sunny SensorBox (SMA Solar Technology AG, Germany) was used. The Sunny SensorBox is installed outside southward, at the angle of 32° in relation to the horizontal surface, and measures the solar irradiation and ambient temperature. The Sunny SensorBox is connected with Sunny WEBBox through SMA Power Injector with Bluetooth. The Sunny SensorBox can collect environmental data from PV solar power plant at FSM which is then used for performance monitoring. Data on Sunny SensorBox are each 5 minutes recorded in WEBBox where their acquisition is performed (Milosavljevic et al., 2015; Pavlovic et al., 2013b). The Sunny SensorBox comes with an integrated solar radiation sensor. There is also the possibility of connecting an ambient temperature sensor and an anemometer to the Sunny SensorBox. Integrated solar radiation sensor used amorphous silicon (a-Si) PV solar cell. Measurement range is 0 W/m² - 1500 W/m², measurement accuracy is ± 8 % and resolution is 1 W/m². Some more information about Sunny SensorBox is given in the paper (Milosavljevic et al., 2015; Pavlovic et al., 2013b; http://files.sma.de/dl/4148/Sensorbox-IEN100914.pdf).

3.2. Measurement of the amount of the electrical energy generated by PV solar power plant

Information on the electrical parameters of the PV solar power plant is provided by Sunny WEBBox. Sunny WEBBox is a communication device with the integrated webserver which through Bluetooth communicates with the inverter - Sunny Boy 2000HF and Sunny SensorBox. Data on PV solar power plant are each 5 minutes recorded in WEBBox where their acquisition is performed. By means of a software in a computer, one can obtain numerical data on a daily, monthly and annual amount of the generated electrical energy (kWh), maximal power (kW), financial amount to obtain by selling electrical energy (Eur) and reduction of CO_2 emission (kg), using PV solar power plant (Milosavljevic et al., 2015; Pavlovic et al., 2013b, http://files.sma.de/dl/11567/SWebBox20-BA-US-CA_en-13.pdf). The inverter and ancillary equipment for the monitoring and data acquisition of PV solar power plant at FSM in Niš, are shown in Figure 3.

Fig. 3 Inverter and ancillary equipment for the monitoring and data acquisition of PV solar power plant at FSM in Niš

3.3. Calculation of the energy efficiency of PV solar power plant

The energy efficiency of PV solar power plant denotes a relation of the electrical energy generated by a PV solar power plant at a certain point of time and the energy of solar irradiation falling on the total surface of solar modules of the PV solar power plant at the same point of time. Considering this, one can talk about instantaneous, hourly, daily, monthly and the annual energy efficiency of the PV solar power plant. A monthly energy efficiency of the PV solar power plant is calculated by means of the Eq. (1) (Milosavljevic et al., 2015; Kymakis et al., 2009; Anser et al., 2013; Pietruszko and Gradzki, 2004):

$$\eta_M = \frac{\sum_{i=1}^{n} (E_D)_i}{S \cdot \sum_{i=1}^{n} (G_{opt})_i} \tag{1}$$

where n is a number of days in a month, E_D is a total amount of the electrical energy generated by the PV solar power plant and transmitted to the power grid during the day (Wh), G_{opt} is a total amount of the global solar irradiation energy falling during the day, on one square meter of the PV solar power plant modules (Wh/m^2), and S is a total solar modules surface (PV array area) (m^2).

3.3.1. Simulation determination of the energy efficiency of a PV solar power plant

A simulation determination of the energy efficiency of a PV solar power plant is conducted by entering into the Eq. (1) data of the middle daily amount of the electrical energy generated by a PV solar power plant and the values of the solar irradiation energy falling on the total surface of a PV solar power plant solar modules. The middle daily amount of the electrical energy generated by a PV solar power plant and the values of the solar irradiation energy falling on the surface oriented southward, at the angle of 32° in relation to the horizontal surface, were obtained by PVGIS-CMSAF software (http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php).

PVGIS (Photovoltaic Geographical Information System –PVGIS © European Communities, 2001–2008) has been developed at the JRC (Joint Research Centre) of the European Commission within its Renewable Energies Unit since 2001 as a research GIS (Geographical Information Systems) oriented tool for the performance assessment of solar PV systems in European, Africa and South-West Asia geographical regions. PVGIS provides data for the analysis of the technical, environmental and socio-economic factors of solar PV electricity generation in mentioned regions. PVGIS is certainly a powerful tool that can be used for the development of the new PV solar power plants that will obviate climate change and promote a sustainable development through the poverty alleviation. The methods used by PVGIS to estimate a PV system output have been described in a number of papers (Pavlovic et al., 2013a; Pavlovic et al., 2013c; Hofierka and Kanuk, 2009; Súri and Hofierka, 2004; Súri et al., 2005; Angelis-Dimakis et al., 2011; Chineke, 2008).

In this paper, PVGIS- CMSAF is used. The PVGIS-CMSAF has been recently introduced using the new databases for the solar radiation data, provided by the Climate Monitoring Satellite Application Facility (CMSAF) in the period 1998-2010 (Pavlovic et al., 2013c).

3.3.2. Experimental determination of the energy efficiency of a PV solar power plant

The experimental determination of the energy efficiency of a PV solar power plant is conducted by entering into the Eq. (1) measurement data of the daily amount of the electrical energy generated by a PV solar power plant and the values of the solar irradiation energy, falling during the day on a PV solar power plant.

4. RESULTS AND DISCUSSION

The results of the simulation and experimental determination of the solar irradiation and energy efficiency of 2 kWp PV solar power plant, installed on the roof of the FSM, University of Niš, in the period from July 1, 2013 until January 1, 2014, are discussed in this section.

4.1. Solar energy

A comparative overview of the simulation and experimental determination results for the monthly values of the global solar irradiation, falling on one square meter of the surface oriented southward, at the angle of 32° in relation to the horizontal surface in Niš, in the period from July 1, 2013 until January 1, 2014, is given in Figure 4.

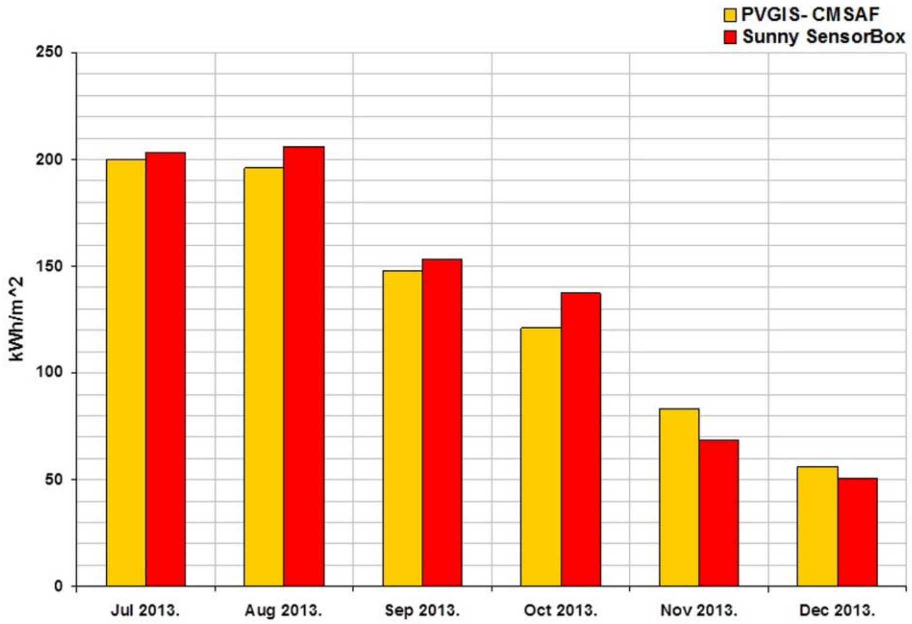

Fig. 4 A comparative overview of the simulation and experimental determination results for the monthly values of the global solar irradiation, falling on one square meter of the surface oriented southward, at the angle of 32° in relation to the horizontal surface in Niš, in the period from July 1, 2013 until January 1, 2014

Figure 4 shows that in the period from July 1, 2013 until January 1, 2014, the experimental monthly values of the global solar irradiation falling on one square meter of the surface oriented southward, at the angle of 32° in relation to the horizontal surface in Niš, ranged from 50.75 kWh/m^2 (in December) to 206.19 kWh/m^2 (in August), while the simulation values ranged from 56.1 kWh/m^2 (in December) to 200 kWh/m^2 (in July). Besides, the total value of the global solar irradiation falling on one square meter of the South-oriented surface, at the angle of 32° in relation to the horizontal surface in Nis, obtained by Sunny SensorBox was 819.39 kWh/m^2 and the value obtained by the PVGIS-CMSAF software was 804.1 kWh/m^2, in the period from July 1, 2013 until January 1, 2014.

4.2. Ambient temperature

A comparative overview of the simulation and experimental determination results for the ambient temperature monthly values in Niš, in the period from July 1, 2013 until January 1, 2014, is given in Figure 5.

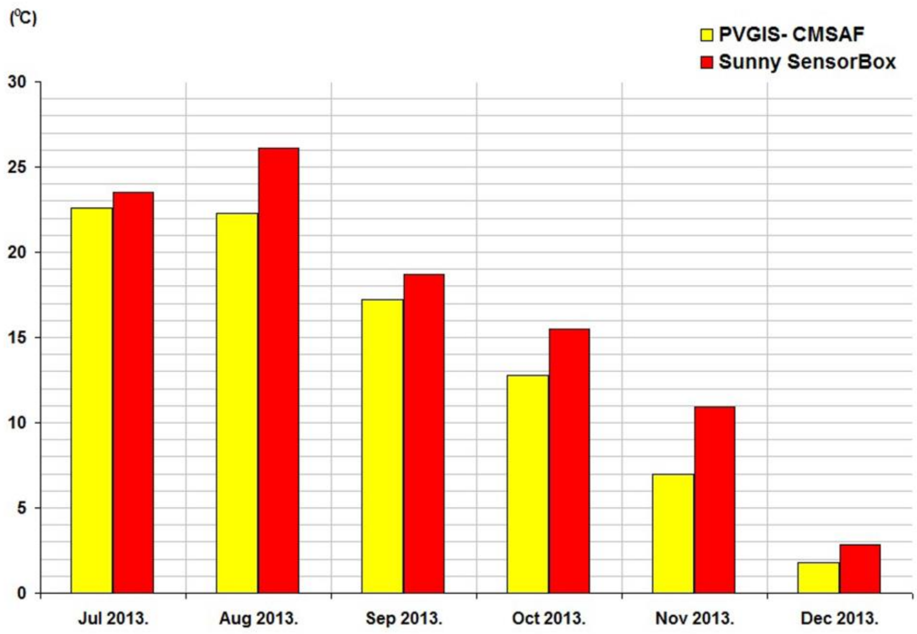

Fig. 5 A comparative overview of the simulation and experimental determination results for the ambient temperature monthly values in Niš, in the period from July 1, 2013 until January 1, 2014

Figure 5 shows that in the period from July 1, 2013 until January 1, 2014, the experimental average monthly values of the ambient temperature in Niš, ranged from 2.8ºC (in December) to 26.1ºC (in August), while the simulation values ranged from 1.8ºC (in December) to 22.6ºC (in July). Besides, in the period from July 1, 2013 until January 1, 2014, the average value of the ambient temperature in Niš, obtained by Sunny SensorBox was 16.26ºC and the value obtained by the PVGIS-CMSAF software was 13.95 ºC.

4.3. Electrical energy generated by the PV solar power plant at FSM in Niš

A comparative overview of the simulation and experimental determination results for the monthly values of the electrical energy generated by the 2 kWp PV solar power plant at FSM in Niš, in the period from July 1, 2013 until January 1, 2014, is given in Figure 6.

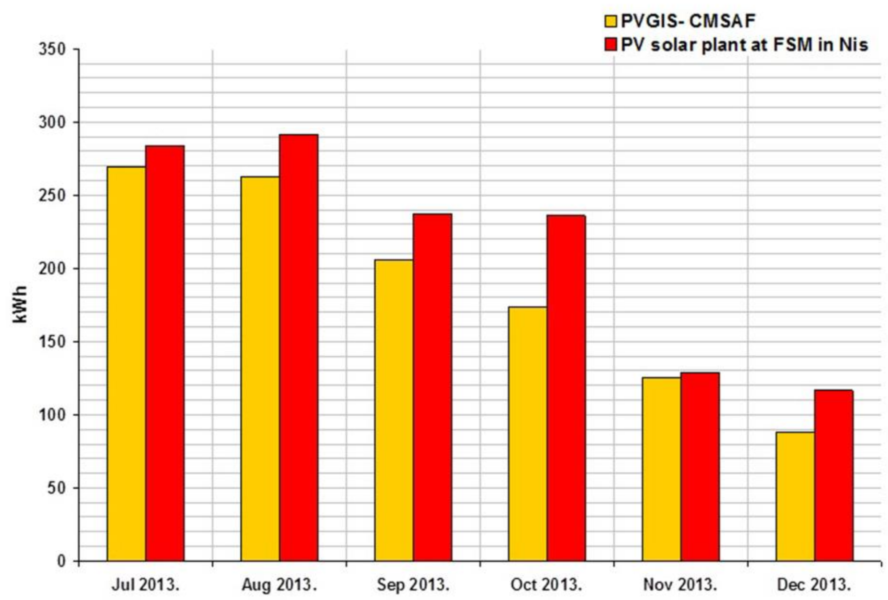

Fig. 6 A comparative overview of the simulation and experimental determination results for the monthly values of the electrical energy generated by the 2 kWp PV solar power plant at FSM in Niš, in the period from July 1, 2013 until January 1, 2014

Figure 6 shows that in the period from July 1, 2013 until January 1, 2014 experimental monthly values of the electrical energy generated by PV solar plant of 2 kWp at FSM in Niš, range from 116.77 kWh (December) to 291.47 kWh (August), while simulation values range from 88 kWh (December) to 269 kWh (July). Besides, total value of the electrical energy generated by PV solar plant of 2 kWp at FSM in Niš, obtained by Sunny WEBBox is 1294.7 kWh and obtained by the PVGIS-CMSAF software is 1125 kWh in the period from July 1, 2013 until January 1, 2014.

4.4. Energy efficiency of the PV solar power plant at FSM in Niš

A comparative overview of the simulation and experimental determination results for the monthly values of the energy efficiency of the 2 kWp PV solar power plant at FSM in Niš, in the period from July 1, 2013 until January 1, 2014, is given in Figure 7.

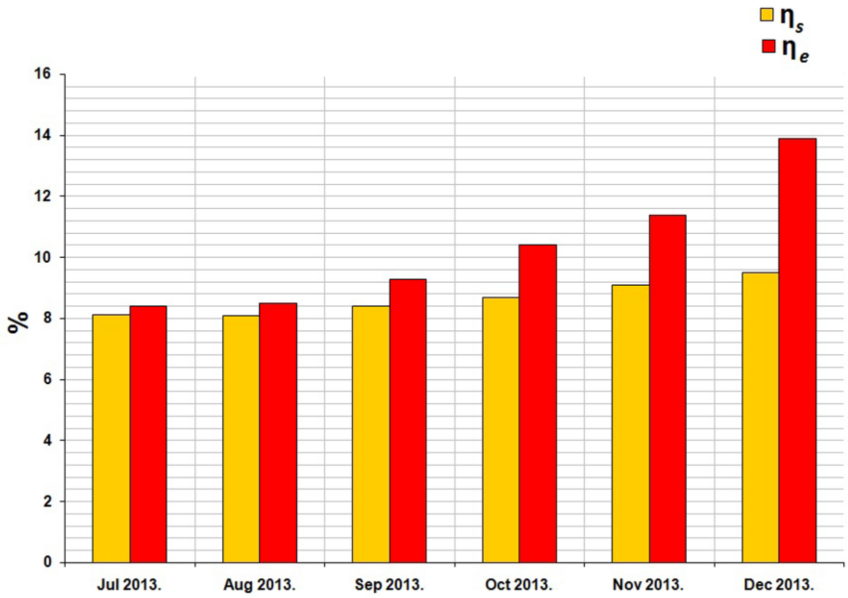

Fig. 7 A comparative overview of the simulation and experimental determination results for the monthly values of the energy efficiency of the 2 kWp PV solar power plant at FSM in Niš, in the period from July 1, 2013 until January 1, 2014 (η_s - simulated energy efficiency, η_e - experimental energy efficiency)

The total values of the global solar irradiation falling on one square meter of the solar modules of PV solar power plant in Niš, obtained by Sunny SensorBox and PVGIS-CMSAF software were 819.39 kWh/m^2 and 804.1 kWh/m^2, respectively, and the total values of the electrical energy generated by PV solar plant in Niš, obtained by Sunny WEBBox and PVGIS-CMSAF software were 1294.7 kWh and 1125 kWh, respectively. Taking into account above mentioned, by simply calculation can be obtained that the six months average values of experimental and simulated energy efficiency of the 2 kWp PV solar power plant at FSM in Niš were: 15.8% and 14%, respectively. However, considering that the PV module surface is 1.659 m^2, the six months average values of the experimental and simulated energy efficiency of the 2 kWp PV solar power plant at FSM in Niš were 9.52% and 8.44%, respectively in the period from July 1, 2013 until January 1, 2014. Besides, in the period from July 1, 2013 until January 1, 2014, the experimental energy efficiency of the 2 kWp PV solar power plant ranged from 8.42% (in July) to

13.87% (in December), while the simulation result of the energy efficiency ranged from 8.08% (in August) to 9.46% (in December), as can be seen in Figure 7.

The energy efficiency of the 2 kWp PV solar power plant at FSM in Niš, versus the ambient temperature, is given in Figure 8.

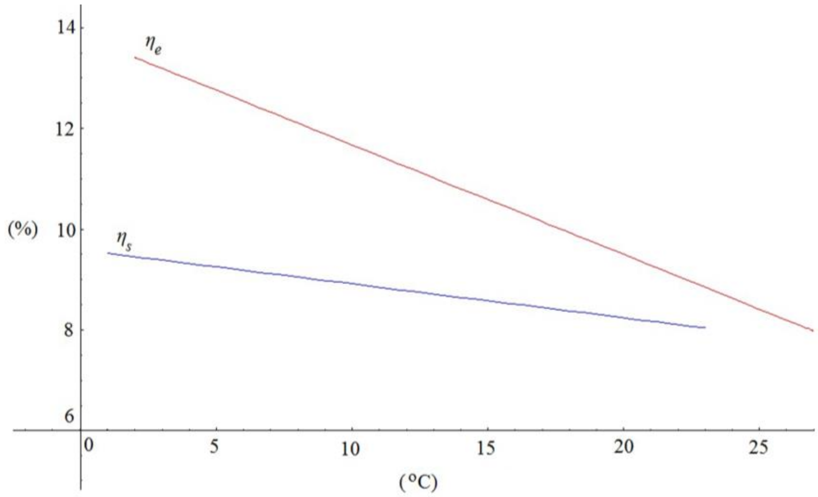

Fig. 8 Energy efficiency of the 2 kWp PV solar power plant versus the ambient temperature (ηs - simulated energy efficiency, ηe - experimental energy efficiency)

With the increase of the ambient temperature there is a linear decrease of the energy efficiency of the 2 kWp PV solar power plant, installed on the roof of the FSM in Niš, as shown in Figure 8. The energy efficiency versus ambient temperature was obtained by a simple linear regression, based on the method of the least squares. Characteristic regression equations are:

$$\eta_e = 13.7184 - 0.215667 \cdot T_{ambe} \quad (2)$$

$$\eta_s = 9.58719 - 0.0671822 \cdot T_{ambPVGIS} \quad (3)$$

where η_e is the experimental energy efficiency and η_s is the simulated energy efficiency of the 2 kWp PV solar power plant, installed on the roof of the FSM in Niš, T_{ambe} is the ambient temperature for Niš, obtained by Sunny SensorBox and $T_{ambpvgis}$ is the ambient temperature for Niš, obtained by PVGIS-CMSAF.

Regression coefficients |–0.215667| and |–0.0671822| in Eq.(2) and Eq.(3), respectively represent the slope in a regression model. Regression coefficient |– 0.215667| in Eq. (2) responds to the average change of the expected value of the dependent variable (η_e) for the unit change of the independent variable T_{ambe}. The data in Figure 8 show that with the increase in the ambient temperature by 1°C, the experimental energy efficiency decreases by 0.22%, in the period from July 1, 2013 until January 1, 2014. Also, regression coefficient |– 0.0671822| in Eq. (3) responds to the average change of the expected value of the dependent variable (η_s) for the unit change of the independent variable $T_{ambpvgis}$ and with the increase in the ambient temperature by 1°C, a simulated energy efficiency decreases by 0.07%, in the period from July 1, 2013 until January 1, 2014.

5. CONCLUSION

In the light of all previously said one can conclude that:

- The total value of the global solar irradiation energy falling on one square meter of the surface oriented southward, at the angle of 32° in relation to the horizontal surface in Niš, obtained by Sunny SensorBox was by 1.9% higher than the total value of the global solar irradiation energy falling on one square meter of the surface oriented southward, at the angle of 32° in relation to the horizontal surface in Niš, obtained by the PVGIS-CMSAF software, in the period from July 1, 2013 until January 1, 2014;
- The average value of the ambient temperature in Niš, obtained by Sunny SensorBox was by 16.85% higher than the average value of the ambient temperature in Niš, obtained by the PVGIS-CMSAF software, in the period from July 1, 2013 until January 1, 2014;
- The total value of the electrical energy generated by the 2 kWp PV solar power plant, installed on the roof of the FSM in Niš, measured by Sunny WEBBox was by 15.08% higher than the total value of the electrical energy generated by the PVGIS-CMSAF software, in the period from July 1, 2013 until January 1, 2014;
- The average value of the experimental energy efficiency of the 2 kWp PV solar power plant, installed on the roof of the FSM in Niš was by 12.8% higher than the average value of the simulation determined energy efficiency, in the period from July 1, 2013 until January 1, 2014;
- The increase in the ambient temperature causes a decrease in the energy efficiency of the 2 kWp PV solar power plant; with the increase in the ambient temperature by 1°C, the experimental energy efficiency decreased by 0.22% and the simulation calculated energy efficiency decreased by 0.07%, in the period from July 1, 2013 until January 1, 2014;
- The decrease of the PV solar power plant energy efficiency occured in summer months due to the increase in the ambient temperatures which in turn caused solar modules heating;
- The difference between the simulation and experimental values of the solar irradiation, ambient temperature, electrical energy generated by PV solar power plant and its energy efficiency, was due to the insufficiently precise approximations which PVGIS software uses to calculate the amount of the electrical energy.

The research results provided in this paper are useful to compare the effective energy production of the PV solar power plants in real climate conditions. Also, the data can prove useful in the planning and operation studies aimed at predicting the impact of the solar energy on the distribution systems, starting by real data and the realistic power generation patterns within different time intervals.

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ISPITIVANJE ENERGETSKE EFIKASNOSTI PV SOLARNE ELEKTRANE NA PRIRODNO-MATEMATIČKOM FAKULTETU UNIVERZITETA U NIŠU

U radu su date osnovne informacije o PV solarnoj elektrani od 2 kWp, sa solarnim modulima od monokristalnog silicijuma, instaliranoj na krovu Prirodno-matematičkog fakulteta (PMF) Univerziteta u Nišu i opremi za ispitivanje njene energetske efikasnosti u realnim klimatskim uslovima. Dati su rezultati eksperimentalno i simulaciono određene energetske efikasnosti PV solarne elektrane na PMF-u u Nišu u periodu od 1. jula 2013. do 1. januara 2014. godine. U tom periodu prosečno određene vrednosti eksperimentalne i simulacione energetske efikasnosti iznosile su 9,52% i 8,44%, redom. Sa povećanjem temperature okoline za 1 °C dolazilo je do pada za 0,22% eksperimentalne i za 0,07% simulaciono određene energetske efikasnosti PV solarne elektrane. Dobijeni rezultati mogu da se koriste prilikom projektovanja PV solarnih elektrana u mestima sa sličnim klimatskim karakteristikama.

Ključne reči: *solarna energija, PV solarna elektrana, energetska efikasnost PV solarne elektrane, PVGIS*