ELECTRICAL ENERGY GENERATION WITH DIFFERENTLY ORIENTED PHOTOVOLTAIC MODULES AS FAÇADE ELEMENTS

by

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In this paper the results of theoretical and experimental investigation of electrical energy generated with differently oriented photovoltaic modules used as façade elements, are presented. It was found that in 2013, optimally oriented monocristalline solar module of 60 Wp generated 62.9 kWh, horizontal module 58.1 kWh, vertical module oriented toward the south 43.9 kWh, vertical module oriented toward the east 25.7 kWh, and vertical module oriented toward the west 22.9 kWh of electrical energy. Also it was found that optimally oriented building integrated photovoltaic system of 1.2 kWp can produce 1081.6 kWh per year; horizontal, vertical oriented toward the south, vertical oriented toward the east, and vertical oriented toward the west can generate 7.6%, 30.2%, 59.2%, and 63.6 less electrical energy, respectively. The greenhouse gas payback periods for the optimally oriented and horizontal building integrated photovoltaic systems were estimated to be 7.8 and 8.5 years, respectively. The obtained results can be applied in designing residential, commercial and other buildings with building integrated photovoltaic systems in Serbia.

Key words: *building-integrated photovoltaic, photovoltaic geographical information system climate monitoring satellite application facility software, photovoltaic electricity generation, greenhouse gas payback period*

Introduction

Of all the renewable energy resources, solar energy is most abundant, inexhaustible and clean. Photovoltaic (PV) technology proved to be one of the best ways to harness the solar power [1, 2]. Growing demand for renewable energy sources has considerably advanced manufacturing of solar cells and PV arrays over recent years [3-5]. The PV solar energy conversion to electricity has been the fastest growing segment of the electricity generation market in the last five years [6].

A building integrated photovoltaic (BIPV) system consists of PV modules integrated into the building envelope, such as the roof or the façade. This technology provides architects with completely new possibilities to incorporate solar technology into buildings. The PV systems and architecture can now be combined into one harmonious mixture of design, ecology,

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and economy. Wide variety of elegant forms, colors and optical structures of cells, glass and profiles enhances creativity and modern architectural design. Solar cells can be incorporated into the façade of a building, complementing or replacing traditional view or spandrel glass. The PV incorporated into awnings and saw-tooth designs on a building façade increase access to direct sunlight while providing additional architectural benefits such as passive shading. The PV shade screens provide a large area for generating electricity and also reduce solar heating in the summer, cutting cooling loads and glare. The PV shade screens can be retrofitted onto existing buildings or integrated into a new buildings design. Using PV for skylight systems is an exciting design feature. By simultaneously serving as the building envelope material and power generator BIPV systems provide savings in materials and electricity costs. Reduce use of fossil fuels and the emission of ozone depleting gases and add architectural interest to the building. The possibility of installing PV generators directly at the point of energy use, and the development of PV modules suited for building integration, make PV an ideal technology for deployment in the urban environment [7-10].

The BIPV generate considerable fractions of urban electricity without the need of dedicating exclusive surface areas for PV plant installations. The building envelope provides the surface area for the PV plant at premium urban locations. In many cases building's electrical installation provides PV plant electrical interface to the public utility grid. Energy is generated at very close proximity to the end user thus avoiding infrastructure investments and losses in transmitting and distributing electrical power [11-18].

When considering BIPV systems, various factors must be taken into account such as shading, installation angle, and orientation. But the most important ones are: available solar irradiation and local weather conditions [19-21]. In the existing literature, there are scarce data regarding the amount of generated electrical energy by PV solar modules in Serbia, especially for PV solar modules with different orientations. Consequently, our research focused on this area, and the results of the measured electrical energy generated by five differently oriented solar modules in real climate conditions in city of Nis, Serbia are presented in this paper. In addition, photovoltaic geographical information system (PVGIS) climate monitoring satellite application facility (CMSAF) software was used for the calculation of the average monthly electrical energy which can be generated by five differently oriented PV modules in Nis and the data were compared. In order to find the energy generation potential of the BIPV systems on a single-family residential house in real climate conditions in Serbia and to assess the feasibility of their application on the buildings in this region, we investigated five differently oriented 1.2 kWp BIPV systems. Using the measurement results, a part of the electrical energy that could be substituted by the refered BIPV systems in relation to the assumed consumption of electrical energy of 350 kWh per month in the average household was calculated based on the measured results.

Worldwide BIPV systems have been increasingly used for the energy independence of the residential and other objects. Therefore, an issue of the electrical energy generated by BIPV systems in relation to their orientations on the objectcs and local climate conditions is of a vital importance. Presented data are important to encourage the application of BIPV systems in Serbia and their power optimization and at the same time can serve as the useful information for neighboring countries with similar climate conditions.

Photovoltaic geographical information system

The PVGIS is a part of the SOLAREC action aimed at contributing to the implementation of renewable energy in the EU. The PVGIS has been developed as the tool for the performance assessment of solar PV systems and an easy estimation of the PV electricity generation potential for the selected specific locations in Europe. The methods used by PVGIS to estimate PV system output have been described in a number of papers [22-24].

The PVGIS software packages can produce following data: average daily, monthly, and yearly values of the solar irradiation taken on square meter of the horizontal surface, or the surface tilted under a certain angle in relation to the horizontal surface, as well as the performances of grid-connected PV systems (free-standing and building integrated) .

The PVGIS-3 data set is based on the measurements made on the ground in the period 1981-1990 which are then interpolated between points to get radiation values at any point. A new version of PVGIS-CMSAF has been recently introduced using the new databases for the solar radiation data provided by the CMSAF from the period 1998-2010 [25-27]. In this paper the PVGIS-CMSAF software was used for the calculation of the average monthly global solar irradiation incident to a horizontal surface, and the average monthly electrical energy which can be generated by five solar modules used in the experiment.

Experiment

The experiment was conducted in the Solar Energy Laboratory at the Faculty of Science and Mathematics at the University of Nis. In order to determine electrical energy generated by five differently oriented solar modules at the same time in real meteorological conditions, an experimental system was constructed, as shown in fig 1.

The experimental system comprises five monocrystalline silicon PV solar modules, each of 60 Wp power and the area of 0.514 m^2. Three solar modules are positioned vertically and oriented towards the east, south, and west, respectively. The fourth module is horizontal and the fifth is oriented towards the south and tilted at the angle of 32°, which is the yearly optimum angle for a fixed solar module in Nis.

The solar radiation intensity, solar energy, and the ambient temperature were measured by DAVIS Vantage Pro meteorological weather station also placed on the roof of the faculty building. A MINI-KLA (Ingenieurburo Mencke & Tegtmeyer GmbH) device was used to measure the current/voltage (I/V) characteristics of each solar module in a rapid succession thus measuring simultaneous behavior of solar modules.

Figure 1. Experimental system composed of five differently-oriented PV solar modules

Results and discussion

The average monthly solar energy measured by DAVIS meteorological weather station in 2013 and average monthly solar energy calculated by PVGIS-CMSAF software, for the horizontal plane, are shown in fig. 2.

Based on the values presented in fig. 2, it can be concluded that the measured values of solar energy received by the horizontal plane are, on average, by 33.4% less than the values calculated by PVGIS-CMSAF software. The difference between the measured and calculated values arises from the fact that PVGIS-CMSAF software gives 12-year averages for the solar energy received by the horizontal plane and that these values are compared to a single year measurement in this experiment.

The measured average monthly electrical energy and the energy calculated by PVGIS--CMSAF for five solar modules in 2013, are given in figs. 3 to 7, respectively.

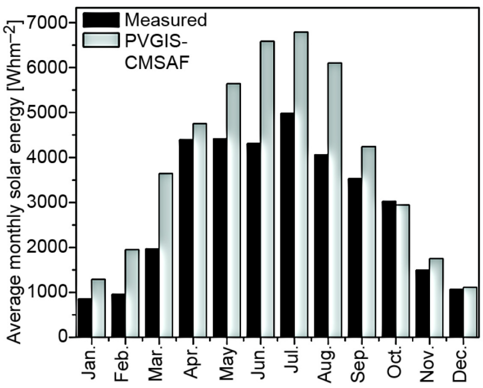

Figure 2. The average monthly solar energy measured by DAVIS meteorological weather station in 2013 and average monthly solar energy calculated by PVGIS-CMSAF software, for the horizontal plane

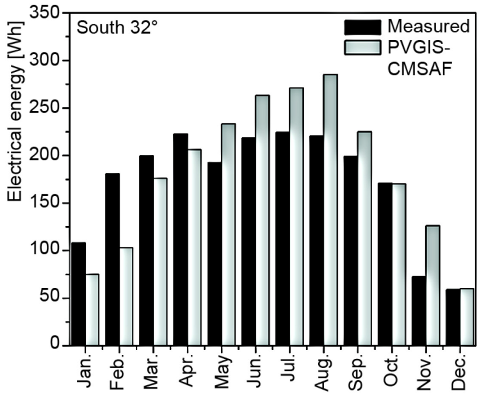

Figure 3. The measured average monthly electrical energy and the energy calculated by PVGIS-CMSAF software for the solar module oriented toward south at the angle of 32° in 2013

It was found that the measured values of the electrical energy generated by the solar module oriented towards the south at the angle of 32° are on average by 1% higher than the values of the electrical energy calculated by PVGIS-CMSAF software. The biggest difference in data was observed in January (44%) and November (42.3%), while the smallest difference was observed in October (0.6%).

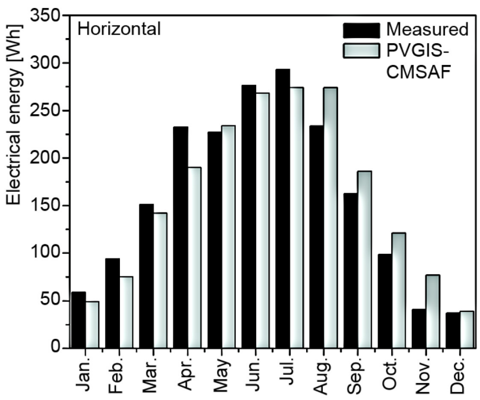

Figure 4. The measured average monthly electrical energy and the energy calculated by PVGIS-CMSAF software for horizontal solar module in 2013

The measured values of the electrical energy generated by the horizontal solar module are on average by 1.4% smaller than the values of the electrical energy calculated by PVGIS-CMSAF software for the same solar module (fig.4). The biggest difference in data was observed in November (47.1%) and the smallest in June (3.1%). From July till October the measured values were greater than the calculated values of the average generated electrical energy, whereas for all other months these values were smaller.

The measured values of the electrical energy generated by the vertical solar module oriented toward the south were on average by 2.1% higher than the values of the electrical energy calculated by PVGIS-CMSAF software. The biggest difference in data was observed in February (57.1%) and November (50.5%) while the smallest difference was observed in September (0.5%) and October (2.6%), respectively.

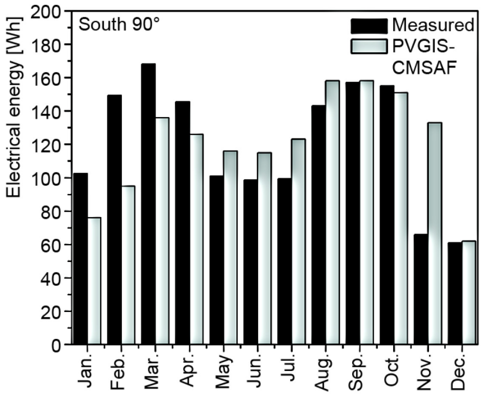

Figure 5. The measured average monthly electrical energy and the energy calculated by PVGIS-CMSAF for the vertical solar module oriented toward south in 2013

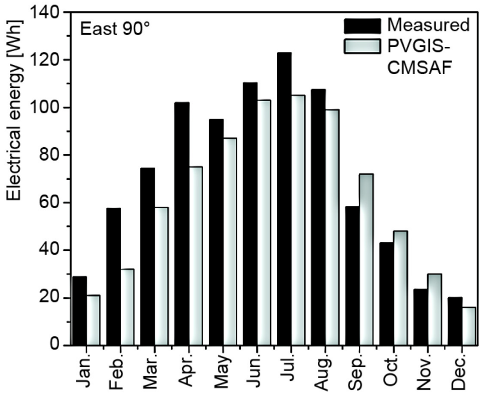

Figure 6. The measured average monthly electrical energy and the energy calculated by PVGIS-CMSAF for the vertical solar module oriented toward east in 2013

The measured values of the electrical energy generated by the vertical solar module oriented toward the east were on average by 16.5% higher than the values of the electrical energy calculated by PVGIS-CMSAF software. The biggest difference in data was observed in February (79.7%) and the smallest in June (7.1%).

The measured values of the electrical energy generated by the vertical solar module oriented toward the west were on average by 3.9% higher than the values of the electrical energy calculated by PVGIS-CMSAF software. The biggest difference in data was observed in February (69.7%) and the smallest in June (5.6%).

Total electrical energy generated by five differently oriented PV modules in 2013 is shown in tab. 1.

As shown in tab. 1 the most of electrical energy was generated by solar module oriented toward the south at the angle of 32° (62.9 kWh), followed by the horizontal solar module (58.1 kWh). Compared to the optimally oriented so-

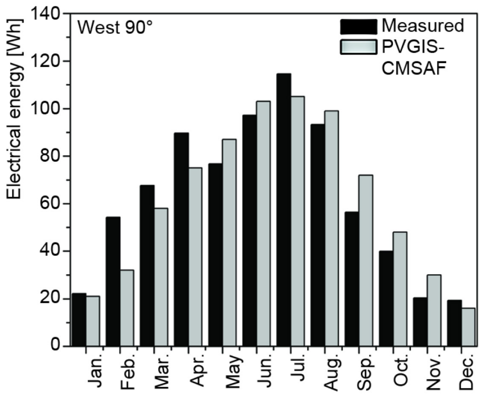

Figure 7. The measured average monthly electrical energy and the energy calculated by PVGIS-CMSAF for the vertical solar module oriented toward west in 2013

Table 1. Total electrical energy generated by five differently oriented PV modules in 2013

	E [kWh]	
Orientation of a PV module	PVGIS-CMSAF	Measured
South 32°	66.8	62.9
Horizontal	58.8	58.1
South 90°	44.1	43.9
East 90°	22.7	25.7
West 90°	22.7	22.9

lar module, the vertical solar modules oriented toward south, east, and west generated by 30.2%, 59.2%, and 63.6% less electrical energy, respectively. The difference in generated electrical energy by the vertical solar modules oriented toward east and west can be attributed to the local climate conditions (afternoon clouds and fog).

For cities and regions for which there are no measured data, it is possible to use, as a guide, the information provided by the PVGIS-CMSAF software.

The BIPV system of 1.2 kWp

The building sector is an important electricity consumer and it is the major factor in the urban environment. With the BIPV technology, solar energy collection is integrated into the building envelope as part of the design. The PV modules serve a dual purpose: they replace conventional building envelope materials and they generate power. While this technology has been incorporated into the design of many new buildings in Europe, it is still not in practice in Serbia.

Over the last few years, the awareness of the significance of solar energy in building design and construction has been gradually increasing. For that reason, a case of five differently oriented 1.2 kWp BIPV systems on a residential single-family building in Serbia are considered. To design a BIPV system with the power of 1.2 kWp, 20 solar modules (ISF-60) should be connected into an array yielding the total surface of 10.28 m^2. This grid-connected BIPV system is composed of solar modules, DC to AC inverter, monitoring system, distribution boxes, switches, and related connections with estimated system losses of 14%.

To calculate the BIPV system average monthly energy, the average monthly electrical energy generated by the five differently oriented solar modules was multiplied by 20 (number of solar modules) and the 14% loss factor was included. The calculated average monthly and total yearly electrical energy which can be generated by five differently-oriented 1.2 kWp BIPV system are given in tab. 2.

Table 2. The calculated average monthly and total yearly electrical energy which can be generated by five differently-oriented 1.2 kWp BIPV systems

Orientation	Average energy [kWh per month]	Total energy [kWh per year]
South 32°	90.1	1081.6
Horizontal	83.3	999.0
South 90°	63.0	755.4
East 90°	36.8	441.6
West 90°	32.8	393.3

Based on the results presented in tab. 2, one can observe that the most of electrical energy can be generated by the BIPV system oriented toward the south at the angle of 32° (90.1 kWh per month) followed by the horizontal BIPV system (83.3 kWh per month).

The average electrical energy consumption per single-family residential home in Serbia is 350 kWh per month. Using the measurement data presented in figs. 3-7, we calculated what percentage of this energy need can be substituted by each of the differently-oriented BIPV systems. The results for the five different orientations of the 1.2 kWp BIPV system are shown in tab. 3.

It should be noted that horizontal 1.2 kWp BIPV system in July can substitute almost half of the monthly electrical energy comsumption of a single-family residential household. In addition, optimally oriented BIPV system can substitute 25.8% of the annual electrical energy comsumption while horizontal BIPV system can substitute 23.8%.

The energy demand of the average residential households in Serbia is compatible with the potential of the energy generation of the optimally oriented 1.2 kWp BIPV system

Table 3. Part of electrical energy in percentages that could be substituted by the BIPV system power of 1.2 kWp in relation to the assumed consumption of the electrical energy of 350 kWh per month in a given residential object for five different orientations of the system, calculated based on the measured results

	Orientation of 1.2 kWp BIPV system				
	Horizontal [%]	South 90° [%]	South 32° [%]	East 90° [%]	West 90° [%]
January	9.0	15.6	16.5	4.4	3.4
February	12.9	20.5	24.9	7.9	7.5
March	23.0	25.6	30.4	11.3	10.3
April	34.3	21.5	32.8	15.0	13.2
May	34.6	15.4	29.3	14.5	11.7
June	40.7	14.5	32.2	16.3	14.3
July	44.6	15.1	34.2	18.7	17.4
August	35.6	21.8	33.6	16.4	14.2
September	24.0	23.2	29.4	8.6	8.3
October	15.0	23.6	26.0	6.6	6.1
November	6.0	9.7	10.7	3.5	3.0
December	5.6	9.3	9.0	3.1	2.9
Average	23.8	18.0	25.8	10.5	9.4

making it suitable for this application. The integration of PV into the buildings in Serbia should be strongly promoted since it provides multiple advantages towards nearly zero energy buildings. Presented data are useful for those who plan to retrofit PV modules on the existing residential objects and those designing BIPV systems for the newly built objects in Serbia.

Greenhouse gas payback period

Greenhouse gas payback time (GPBT) is used to measure the PV system or PV technology sustainability especially when the whole world is tackling the global warming problems by reducing emission of greenhouse gases (GHG) for environmental protection. A PV system does not generate CO_2 during the operation. However, CO_2 and other gases are generated during its entire lifecycle such as extraction, production and disposal processes. Therefore, it is important to study the payback period based on the GHG emission to determine the sustainability of the PV system. The most common way to express the GHG emission is using the unit of kg CO_2 equivalent, [kg CO_{2eq}], which is a weighted mass sum of emissions such as CO_2, CH_4, and NO_2.

The environmental benefit of a BIPV system can be assessed using the GPBT exppressed by eq. (1):

$$\mathrm{GPBP} = \frac{\mathrm{GHG_S} + \mathrm{GHG_{BOS}}}{\mathrm{GHG_{output}}} \tag{1}$$

where $\mathrm{GHG_S}$ is the embodied GHG of the system (PV modules), $\mathrm{GHG_{BOS}}$ – the embodied GHG of the balance of system (BOS), and $\mathrm{GHG_{output}}$ – the annual GHG reduction if the power is generated by BIPV system instead of from the local power company, all expresed in [kg CO_{2eq}]. For the GHG_S produced during the cell fabrication processes, 463 kg CO_{2eq}/m^2 is assumed [28]. The BOS encompasses all components of a PV system other than the PV modules; this includes supporting structure, inverter, and cabling. Regaring the BOS for rooftop installations, 125 kg CO_{2eq}/m^2 is used for the inverters and 6.1 kg CO_{2eq}/m^2 is used for the array support and cabling [29].

Based on [30] GHG reduction is calculated:

$$GHG_{output} = \text{Generated electrical energy} \times CO_2 \text{ avoidance factor}$$

For Serbia CO_2 avoidance factor is 0.72 kg CO_2/kWh [31]. For a BIPV system power of 1.2 kWp and surface of 10.28 m^2, regardles of its orientation, GHG_S, GHG_{BOS}, and their sum are:

$$GHG_S = 463 \text{ kg } CO_{2eq}/m^2 \times 10.28 \text{ m}^2 = 4759.64 \text{ kg } CO_{2eq}$$

$$GHG_{BOS} = (125 \text{ kg } CO_{2eq}/m^2 + 6.1 \text{ kg } CO_{2eq}/m^2) \times 10.28 \text{ m}^2 = 1347.71 \text{ kg } CO_{2eq}$$

$$GHG_S + GHG_{BOS} = 6107.35 \text{ kg } CO_{2eq}$$

Calculated GPBP for differently oriented BIPV systems of 1.2 kWp is given in tab. 4.

Table 4. The GPBP for differently oriented BIPV systems of 1.2 kWp

Orientation of 1.2 kWp BIPV system	Total generated electical energy [kWh per year]	GHG_{output} [kg CO_{2eq}]	GPBP [year]
South 32°	1081.6	778.7	7.8
Horizontal	999.0	719.3	8.5
South 90°	755.4	543.9	11.2
East 90°	441.6	317.9	19.2
West 90°	393.3	283.2	21.6

Based on the results presented in tab. 5 it can be seen that the optimally oriented 1.2 kWp BIPV system, south 32°, would have the smallest GPBP (7.8 years) followed by the horizontal 1.2 kWp BIPV system with GPBP of 8.5 years.

Conclusions

In the light of all the presented, it can be concluded that:

- Experimentally obtained values of the solar energy received by the horizontal plane in 2013 are on average by 33.4% less than the energy values calculated by PVGIS-CMSAF software.
- Optimally oriented monocrystalline solar module of 60 Wp in 2013 generated 62.9 kWh, horizontal module 58.1 kWh, vertical module oriented toward the south 43.9 kWh, vertical module oriented toward the east generated 25.7 kWh, and vertical module oriented toward the west generated 22.9 kWh of electrical energy.
- Difference between the theoretical and experimentally obtained values of the generated electrical energy in 2013 by five differently oriented modules ranges from 1.0 to 16.5%.
- Optimally oriented BIPV system of 1.2 kWp can produce 1081.6 kWh per year. Horizontal, vertical oriented toward the south, vertical oriented toward the east, and vertical ori-

ented toward the west BIPV system can generate 7.6%, 30.2%, 59.2%, and 63.6 % less electrical energy, respectively.

- Optimally oriented and horizontal BIPV systems of 1.2 kWp can substitute 25.8% and 23.8% of the average annual electrical energy comsumption of a single-family residential household in Serbia.
- The GPBP for the optimally oriented and horizontal BIPV systems were estimated to be 7.8 and 8.5 years, respectively. For the vertical BIPV systems oriented toward the south, east, and west, GPBP were estimated to be 11.2, 19.2, and 21.6 years, respectively.

Since BIPV systems are very rare in Serbia, this paper gives valuable information on how different positions and orientations of PV modules on the building envelope can modify their energy production. The obtained results can be applied for designing residential, commercial and other buildings with BIPV systems in Serbia.

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