A PRACTICAL FIELD STUDY OF PERFORMANCES OF SOLAR MODULES AT VARIOUS POSITIONS IN SERBIA

by

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Results of practical field study of performances of three identical monocrystalline solar modules, single power of 60 W, with different inclinations (horizontal, optimally inclined oriented toward south, and vertically oriented toward south) in real meteorological conditions, in city of Nis, Serbia, in 2013, are presented in this paper. On the basis of the measurement results of solar energy intensity and electrical power generated with solar modules, efficiency, performance ratio, and fill factor were calculated. In 2013, optimally inclined solar module generated 62.8 kWh, horizontal solar module 58.1 kWh, and vertical solar module 43.9 kWh of electrical energy. It was found that annually the vertical solar module had the highest value of efficiency (10.9%), then horizontal solar module (10.6%) and finally, optimally inclined solar module (10.2%). Annually, the vertical solar module had the highest value of performance ratio (0.93), then follows horizontal solar module (0.91) and finally, optimally inclined solar module (0.86). Annually, the horizontal solar module had the highest value of fill factor (67.7), then follows vertical solar module (66.6) and, finally, optimally inclined solar module (63.3). It was found that embodied energy payback time for a horizontal, optimally inclined, and vertical building-integrated photovoltaics system of 1020 Wp would be 11.8, 10.9, and 15.6 years, respectively. The results obtained by this study could be used in planning and constructing building-integrated photovoltaics, in Serbia.

Key words: *outdoor testing, performance ratio, photovoltaic efficiency, fill factor*

Introduction

The continuous growth of energy demand from all around the world has urged the society to seek alternative energy sources due to the depletion of conventional energy resources and their undesirable impact on environment. Among the available alternative energies, photovoltaic (PV) energy is one of the most promising renewable energies. The PV energy is clean, simple in design, and requires very little maintenance [1, 2].

The performance of PV modules under actual outdoor conditions is found to be quite different from that determined under controlled laboratory conditions [3-9]. Performance of PV modules will not be the same for a given PV module if it is located in places with different climate types *e. g.* wet tropical, dry desert, or continental climate. Amin *et al.* [10] conducted a practical field study of various solar cell performances in Malaysia and concluded that

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monocrystalline silicon modules are not the best solution for Malaysia's weather conditions. Carr and Pryor [11] confirmed a strong seasonal variation in the performance of crystalline modules with a clear improvement in colder months. This is supported by Aika *et al.* [12] whose analysis of the monthly performance ratio (PR) indicated that the monocrystalline silicon modules showed low performance in summer and high performance in winter. Bashir *et al.* [13], based on experimental investigation in Pakistan, reported that monocrystalline silicon modules are more efficient than other modules, but have shown a higher decrease at higher module temperatures. Gxasheka *et al.* [14] measured and analyzed performance parameters of five PV modules during three stages of a 17-month test period. They also investigated effect of temperature and irradiance on the performance parameters.

Solar irradiance has the greatest impact on the power output of a PV system [15-17]. Module temperature has significant influence on the behavior of a PV system, as it modifies system efficiency and output energy. It is influenced by the ambient temperature, cloud patterns, and wind speed [18, 19]. The effect of the temperature of the PV module on its efficiency has been widely studied [20-26].

Several authors have studied the efficiency of electric conversion of PV modules as a function of climate conditions for specific locations. Furushima *et al.* [27] have performed a detailed experimental study for city of Kumamoto, Japan. Nordmann and Clavadestcher [28] compared the effects of module temperature, environmental temperature, and type of assembly for 18 PV across five different countries.

The PV characteristics (or I-V curve) of a PV module is the important key for identifying its quality and performance as a function of varying environmental parameters [29, 30]. The curve indicates the characteristic parameters of the PV module at which it would work at peak efficiency. These parameters are indispensable for designing any small or large PV system. Therefore, it is of utmost importance to measure the I-V characteristics with high accuracy under natural environmental conditions [31].

It is important to be familiar with the basic features for a given type of solar modules for local meteorological conditions, since they are significantly site-dependent. Studies focusing on the local climatic variables become more relevant and determinant for the economic feasibility of investment in installing PV power plants [32-34].

The main objective of this study was to compare the performances of horizontal, vertical, and optimally inclined monocrystalline PV modules in real meteorological conditions in city of Nis, Serbia. Solar modules in these three positions can be easily applied in modern architecture in urban settings.

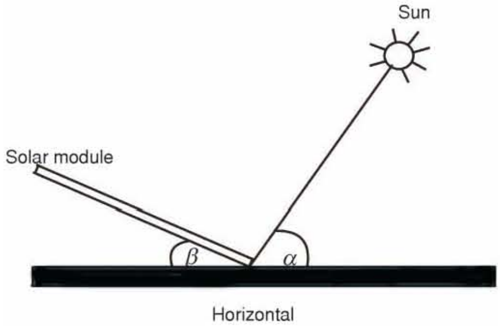

Figure 1. The tilt angle of the module β and the elevation angle α

Solar radiation on a PV module

The power incident on a PV module depends not only on the power contained in the sunlight, but also on the angle between the module and the Sun rays (fig. 1). When the absorbing surface and the sunlight are perpendicular to each other, the power density on the surface is equal to that of the sunlight.

If the solar radiation measured on horizontal surface G_{horiz} is known then the amount of solar radiation incident on a tilted module surface G_{module} can be calculated using eq. (1).

$$G = \frac{G_{\text{horizontal}} \sin(\alpha + \beta)}{\sin\alpha} \tag{1}$$

where α is the elevation angle, and β – the tilt angle of the module measured from the horizontal surface. The elevation angle α is:

$$\alpha = 90 - \varphi + \delta \tag{2}$$

where φ is the latitude and δ – the declination angle given as:

$$\delta = 23.45° \sin\left[\frac{360}{365}(284 + d)\right] \tag{3}$$

where d is the day of the year [35].

Efficiency

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another, *i. e.* one PV module to another. Efficiency (η) is defined as the ratio of energy output from the module to input energy from the Sun.

The efficiency of a PV module is:

$$\eta_{\text{m}} = \frac{P_{\text{measured}}}{G_{\text{measured}} S} \cdot 100 \tag{4}$$

where P_{measured} [W] is the measured power output, G_{measured} [Wm^{-2}] – the measured solar irradiance intensity, and S [m^2] – the active area of solar module.

The efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another. Solar panels are affected by their operating temperature and the parameter most affected by an increase in temperature is the open-circuit voltage. Change in solar modules efficiency is a result of a combination of solar irradiance intensity, ambient temperature, elevation angle of the Sun, and local weather conditions [11, 13].

Performance rating

There are many methods of analyzing the performance of PV modules. The increasingly common measure of energy production is the PR.

The general equation for PR is:

$$PR = \frac{P_{\text{measured}}}{P_{\max(\text{STC})}} \frac{G_{(\text{STC})}}{G_{\text{measured}}} \tag{5}$$

where P_{measured} [W] is the measured power output, $P_{\max(\text{STC})}$ – the maximal rated power at standard test conditions (STC), $G_{(\text{STC})}$ – the solar irradiance intensity of 1000 W/m^2, and G_{measured} [Wm^{-2}] – the measured solar irradiance intensity. The PR is a site-dependent parameter, which does not take into account temperature or spectral effect. However, it does enable a quantitative comparison of different technologies for a given climate [10, 11, 13, 36].

Fill factor

Product of voltage and current in any given point of I-V characteristics is always less than the product of open-circuit voltage V_{oc} and short-circuit current I_{sc}. For an optimal operating point, for which the power is maximal, the ratio

$$\mathrm{FF} = \frac{V_{\mathrm{MP}} I_{\mathrm{MP}}}{V_{\mathrm{OC}} I_{\mathrm{SC}}} \tag{6}$$

is always less than one. The V_{MP} is the maximal power voltage (the voltage where a module outputs the maximum power) and I_{MP} is the maximum power current, the maximum amperage where a module outputs the maximum power. This ratio is known as fill factor (FF). The FF shows the influence of the serial resistance on efficiency of solar cell, in other words, it shows how much the solar cell is close to ideal one [11, 13].

Experiment

The experiment was conducted in the Solar Energy Laboratory of the Faculty of Science and Mathematics, University of Nis, Nis, Serbia. Three monocrystalline silicon PV solar modules, with single power 60 W and the area of 0.514 m^2 were used in this study tab. 1. The yearly optimum inclination angle for a fixed solar module in city of Nis (43.3 N, 21.9 E) was determined by classic PVGIS and is $\beta = 32°$ [37]. The first module was horizontally positioned (horizontal). The second was oriented towards the south and tilted at the optimal angle of 32° (optimally inclined). The third solar module was positioned vertically and oriented toward the south (vertical). The system was placed on the roof of the Faculty building in city of Nis.

Table 1. Technical characteristics of solar module ISF-60/12

Outside dimensions (size)	776 × 662 × 39.5 mm
Weight	6.5 kg
Cell type	Si monocrystalline
Power of the module	60 Wp
Module efficiency	11%
Maximum power current	3.47 A
Maximum power voltage	17.3 V
Open circuit voltage	21.6
NOCT (800W/m^2, 20°C, AM 1.5, 1 m/s)	47°C
Maximum system voltage	760 V

For the measurement of I-V characteristics of solar modules a Mini-KLA device (Ingenieurbüro Mencke & Tegtmeye, Germany) was used. By using Mini-KLA device, V_{MP}, I_{MP}, P_{MP}, V_{oc}, I_{sc}, and FF, for each solar module, were practically instantaneously measured and I-V characteristics were traced. The measurements were performed every half an hour during the day. The solar irradiance intensity, solar energy as well as ambient temperature were measured by DAVIS Vantage Pro (USA) meteorological weather station.

Results and discussion

Daily changes of parameters

In order to show the difference in the parameters of the three PV modules during different seasons, two sunny days, one in winter and one in the summer were selected. The results of the daily change of ambient temperatures and solar radiation intensities for these two day are presented.

The change of solar irradiance intensity for the three positions of solar modules during February 5, 2013 is shown in fig. 2. The solar irradiance intensity on horizontal plane was measured, while for planes oriented toward south at the angle of 32º and 90º, it was calculated using eq. (1).

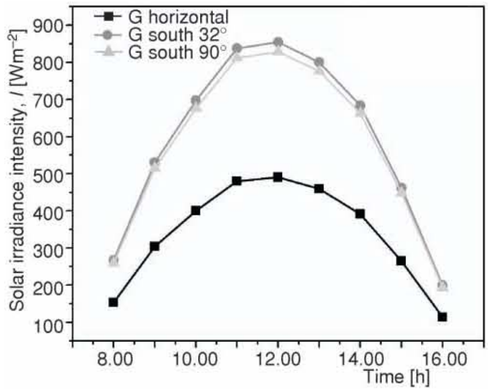

Figure 2. Change of solar irradiance intensity for three positions of solar modules during 05.02.2013

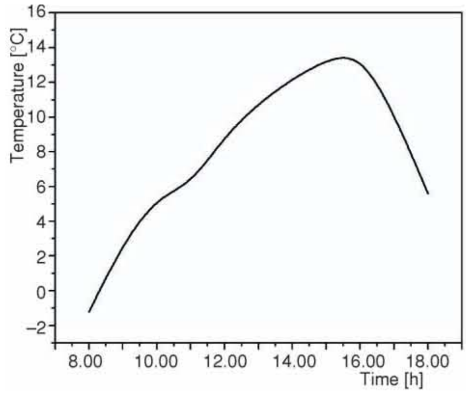

Figure 3. Change of ambient temperature during 05.02.2013

On February 5, 2013, the most of solar irradiance was received by optimally inclined solar module ranging 267-850 W/m^2, then by the vertical solar module 260-830 W/m^2, while the horizontal solar module received the least amount of solar irradiance 150-490 W/m^2. On this day, the elevation angle of the Sun was $\alpha = 30.6°$ and declination angle was $\delta = -16.4°$.

The change in ambient temperature during February 5, 2013 is shown in fig. 3.

It can be observed from fig. 3. that the ambient temperature during the day of 05.02.2013 changed from –1.2 °C to 13.7 °C.

Under these conditions, during the day, the optimally inclined solar module generated 333.8 Wh, the vertical solar module 303.9 Wh, and the horizontal solar module 150.5 Wh of electrical energy.

For calculating efficiency of all three solar modules eq. (4) was used. The change in the efficiency of solar modules during 05.02.2013 is shown in fig. 4.

As it can be seen in fig. 4, the efficiency of optimally inclined solar module was higher in the morning (17.0%) and evening (15.0%) than at high noon (10%). Similarly, the efficiency of the vertical solar module was also higher in the morning (16.4%) and evening (16.5%) than at high noon (9.4%). These differences in the efficiency of the modules are the consequence of the fact that the morning and evening ambient temperatures were lower than the temperature at noon and that the solar irradiance intensity incident to the optimally inclined and the vertical module was above 800 W/m^2 at noon. The change of the efficiency for the horizontal solar module was low, between 9.8% and 11.3%, because during this day the ambient temperature and the solar irradiance intensity incident to the horizontal solar module were low. Moreover, the solar irradiance incident to the horizontal module was too low at 8:00 and 16:00 hours, therefore it was not possible to determine the module's efficiency.

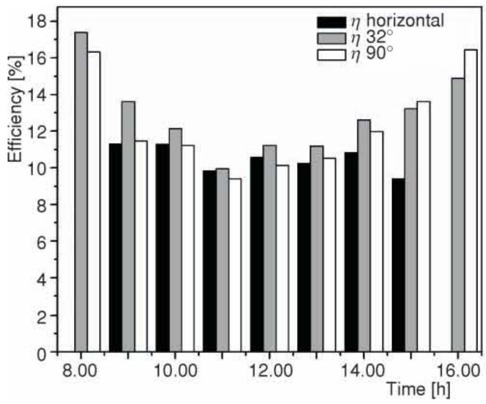

Figure 4. Change of efficiency of solar modules during 05.02.2013

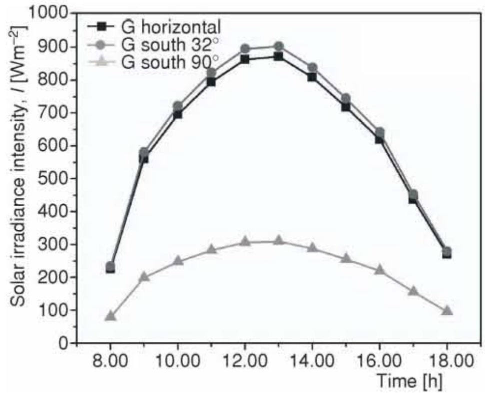

Figure 5. Change of solar irradiance intensity for three positions of solar modules during June 19, 2013

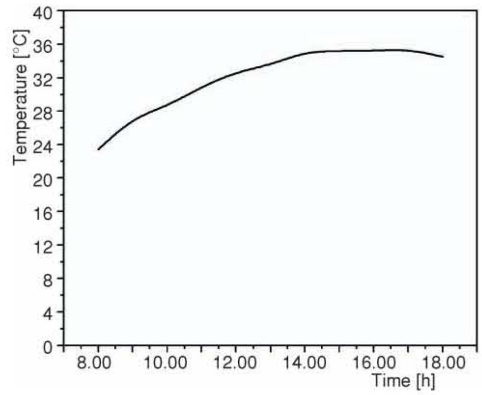

Figure 6. Change of ambient temperature during June 19, 2013

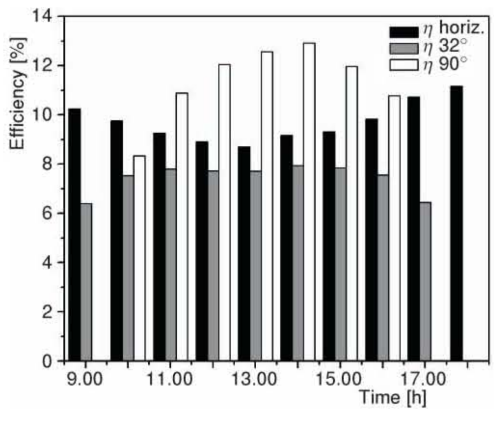

Figure 7. Change of efficiency of solar modules during June 19, 2013

By measurements performed by Mini-KLA device on February 5, 2013 at 13.30 hours following results were obtained: V_{MPP} = 16.6 V, I_{MPP} = 1.50 A, P_{MPP} = 24.9 W, V_{OC} = 20.9 V, I_{sc} = = 1.63A, and FF = 56.2.

The change of the solar irradiance intensity for the three positions of solar modules during June 19, 2013 is shown in fig. 5.

The most of solar irradiance, during June 19, 2013, was received by optimally inclined solar module 233-903 W/m^2, and then by horizontal solar module 225-870 W/m^2. As expected, vertical solar module received the least solar irradiance 80-310 W/m^2. On this day the elevation angle of the Sun was α = 70.43° and the declination angle was δ = 23.43°.

The change in ambient temperature during June 19, 2013 is shown in fig. 6.

In fig. 6. it can be observed that ambient temperature during June 19, 2013 changes from 23 °C to 34 °C.

Under these conditions, during the day, horizontal solar module generated 348.9 Wh, optimally inclined 267.4 Wh, and vertical solar module 112.4 Wh of electrical energy.

The change in the efficiency of solar modules during June 19, 2013 is shown in fig. 7.

As shown in fig. 7, the efficiency of the horizontal module ranges from 9% to 10% during the day. For the optimally inclined module is between 6-8% and for the vertical one is 8-12%. The vertical solar module achieved the efficiency of 8-12 % due to the high ambient temperature and low incident solar radiation (~300 W/m^2 at noon). It should be noted that all three modules had efficiency below STC (11%), except vertically inclined module in early afternoon.

By measurements performed by Mini-KLA device on June 19, 2013 at 13.30 hours following results were obtained: V_{MPP} = 12.1 V, I_{MPP} = = 3.23 A, P_{MPP} = 39.1 W, V_{OC} = 18.3 V, I_{sc} = = 3.80 A, and FF = 56.2.

Results have shown that the efficiency of all three modules was higher in winter day (February 5) than in summer day (June 5). This can be explained by the fact that the module is more efficient when the ambient temperature is low and that their efficiency diminishes at high temperatures. The daily change in the efficiency of optimally inclined solar module, during winter day, had peaks in the morning and evening, and slight dip in the middle of the day. While, in summer day, efficiency of optimal module had a slight increase at high noon. The daily change in the efficiency of the horizontal module, in winter, was not affected much by the change of temperature and solar irradiance because there values were small. The decrease in efficiency of horizontal module was evident at high noon in summer day. In winter day, efficiency of vertical solar module decreases at high noon, whereas, in summer day efficiency peaks at high noon. The changes in temperature and solar irradiance incident to the vertical module were opposite for these two days.

Annual changes of parameters

The changes of following parameters were considered: solar irradiance intensity, solar energy, generated electrical energy, efficiency, PR, FF, and ambient temperature.

The change of maximal daily solar irradiance intensity during the year 2013 is shown in fig. 8.

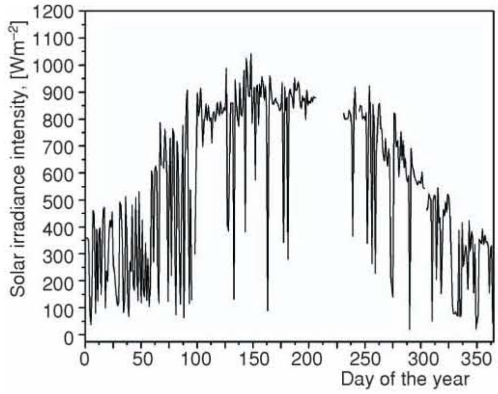

Figure 8. Change of maximal daily solar irradiance intensity for year 2013

The maximum values of the solar irradiance intensity in January, February, November, and December were below 540 W/m^2. In the same period one can notice a lot of peaks because there were a lot of cloudy days. From the beginning of March, the maximum intensity of solar irradiance increased until the beginning of August reaching around 900 W/m^2 and then during September and October continually decreased to the approximately 400 W/m^2. The highest value of solar irradiance was recorded in May and it measured 1046 W/m^2.

The solar energy on horizontal plane was measured, while for planes oriented toward South at the angle of 32° and 90°, it was calculated using eq. (1). Due to malfunction of the meteorological station, no data were recorded between 16th of July and 18th of August.

The average monthly measured values of incident solar energy on horizontal solar module and calculated values of incident solar energy on optimally inclined and vertical solar module, in year 2013, are shown in fig. 9.

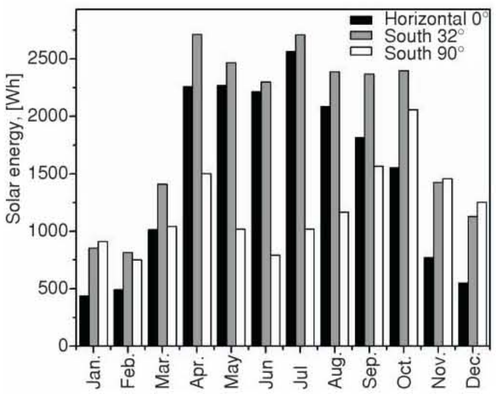

Figure 9. The average monthly measured values of incident solar energy on horizontal module and calculated values of incident solar energy on optimally inclined and vertical solar modules in year 2013

The measured incident solar energy on the horizontal module increased from the minimum value in January (438 Wh) to its maximum value in June (2562 Wh). From April until August, the solar energy values were above 2000 Wh, and from September until December gradually decreased to 550 Wh.

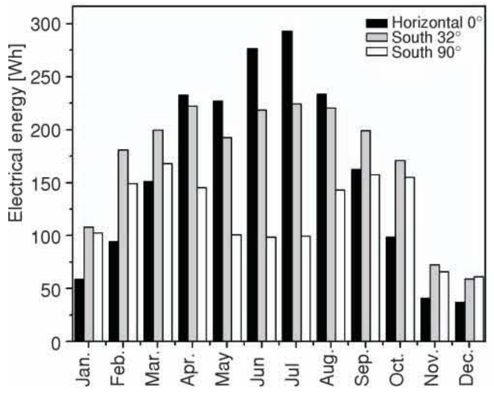

Figure 10. Measured average monthly electrical energy generated by three solar modules in year 2013

The calculated solar energy incident on the optimally inclined solar module increased from its minimum value in January (816 Wh) to its maximum value in April (2713 Wh). Then, from May until October, it had values around 2300 Wh with exception of June when that value was 2711 Wh. The solar energy values significantly decreased in November and December (1130 Wh). Annually, the most of solar energy was received by optimally inclined solar module.

The calculated solar energy incident on vertical solar module changed from minimal values in January and February (752 Wh) to the first maximum in April (1502 Wh). Then, its values decreased until the summer minimum in June (793 Wh) and, again, increased to the second maximum in October (2060 Wh). After that, the values decreased in November and December (1253.8 Wh).

The measured average monthly electrical energy generated by the three solar modules in year 2013 is shown in fig. 10.

The average monthly electrical energy generated by horizontal solar module increased from the minimum value in January (58.8 Wh) to the maximal value in July (293 Wh). From April until August, the values of generated energy were above 220 Wh. From September to December, the values of generated energy decreased to the minimum of 37 Wh.

The value of average monthly electrical energy generated by the optimally inclined solar module increased from 108 Wh for January to 222.5 Wh for April. In May, the value of average monthly generated electrical energy had a slightly lower value of 192 Wh, and then from June to September, the values of generated electrical energy were above 200 Wh. The value of the generated energy in October (171 Wh) slightly decreased and reached a minimum value in November and December (59 Wh). Optimally inclined module generated less electrical energy in summer months because the increase of ambient temperature increases the solar module temperature and reduces its efficiency.

The electrical energy generated by the vertical solar module had two maximums: one in March (168 Wh) and the other one in September (157 Wh). The minimum values of generated electrical energy were in December (61 Wh) and June (100 Wh.)

In June, the horizontal solar module generated on average 4.7 times more electrical energy than in January, while optimally inclined solar module generated two times more electrical energy than in January. The horizontal solar module generates the most electrical energy in July, while the optimal solar module does in April. The vertical solar module generates the most of electrical energy in March. In year 2013, the optimally inclined solar module generated 62.8 kWh, horizontal solar module 58.1 kWh and vertical solar module 43.9 kWh electrical energy.

The efficiency and PR of modules were calculated based on eqs. (4) and (5), respectively, using measured electrical power output as well as measured and calculated solar energy incident on these three modules. The average monthly efficiency, PR and FF for horizontal solar module, solar module at optimal angle, and vertical solar module, as well as average monthly ambient temperature, in year 2013 are given in tab. 2.

Table 2. Average monthly efficiency, PR and FF for horizontal solar module, solar module at optimal angle, and vertical solar module as well as average monthly ambient temperature, in year 2013

	$\eta_{hor.}$ [%]	η 32° [%]	η 90° [%]	$PR_{hor.}$	PR 32°	PR 90°	$FF_{hor.}$	FF 32°	FF 90°	t [ºC]
January	13.0	13.3	11.6	1.12	1.14	0.99	73.1	65.0	66.9	2.8
February	11.8	12.7	12.2	1.00	1.10	1.04	74.0	66.6	69.0	5.1
March	11.4	12.6	12.2	0.97	1.09	1.05	71.5	62.9	66.4	6.3
April	11.1	9.6	11.1	0.95	0.81	0.98	66.1	64.0	69.0	14.0
May	11.3	8.1	9.8	0.91	0.64	0.63	63.2	63.0	69.1	18.7
June	9.7	7.9	11.4	0.92	0.60	0.97	62.7	62.6	68.5	20.4
July	10.4	7.4	11.1	0.89	0.63	0.95	64.2	63.8	69.3	21.1
August	9.4	7.7	8.2	0.80	0.66	0.79	62.4	59.5	64.8	23.4
September	10.7	9.6	11.1	0.91	0.82	0.95	66.6	66.1	61.4	17.2
October	9.6	11.0	11.5	0.82	0.94	0.98	69.4	63.1	65.5	14.8
November	9.0	10.7	10.0	0.78	0.91	0.86	70.3	62.8	63.7	10.0
December	9.7	12	10.8	0.83	1.02	0.92	68.4	63.6	65.5	1.9
Average	10.6	10.2	10.9	0.91	0.86	0.93	67.7	63.6	66.6	13.0

Based on the data given in tab. 2, it can be also observed that the vertical solar module had annually the highest value of efficiency (10.9%), followed by the horizontal solar module (10.6%), and finally the optimally inclined solar module (10.2%).

Based on the data given in tab. 2, it can be also observed that annually the vertical solar module had the highest value of PR (0.93), then horizontal solar module (0.91), and optimally inclined solar module (0.86). The PR is in direct correlation with the solar modules efficiency and this is the reason why the PR values changed as efficiency changed. Similar PR values (greater than 1) have been obtained and reported by Amin *et al.* [10] and Del Cueto [38]. They obtained those values using the equation which was used in this paper as well (eq. 4). The PR values greater than 1 were calculated when measured values of solar irradiance were lower than STC 1000 W/m^2.

From the data shown in tab. 2, it can be observed that the horizontal solar module annually had the highest value of FF (67.7), then the vertical solar module (66.6), and the optimally inclined solar module (66.3).

The average yearly value of ambient temperature was 13.0 °C. In winter months, the average monthly ambient temperature was between 1.9 °C and 5.1 °C, and during the summer months between 20.4 °C and 23.3 °C

Considering the annual changes of parameters, a strong seasonal variation is apparent in performances of monocrystalline modules. This is supported by the same observation by Carr and Pryor [11], who also observed the improvement in performances in the cooler months when the ambient temperatures were lower.

Differently oriented building-integrated photovoltaic system of 1020 Wp

Single-family homes in residential suburbs can be considered most suitable for application of building-integrated photovoltaics (BIPV), due to their typically large roof areas and energy demand much more compatible with the energy generating potential of BIPV. Our goal was to find out how much electrical energy can be generated by horizontal, optimally-inclined, and vertical BIPV systems in real meteorological conditions in Serbia. We propose to use a BIPV system of 1020 Wp power that consists of 17 solar modules (ISF-60/12), when connected into an array the surface would be 8.74 m^2.

Based on the experimental data reported in this paper, we can calculate that the amount of average monthly electrical energy which can be generated by horizontal, optimally inclined, and vertical BIPV systems of 1020 Wp in year 2013 would be 82.2 kWh per month, 89.1 kWh per month, and 62.2 kWh per month, respectively. The average electrical energy consumption per single-family residential home in Serbia is 350 kWh per month. Hence, in year 2013, the horizontal, optimally-inclined or vertical BIPV system, could be able to substitute for 23.5%, 25.4% or 17.9%, respectively, of the average energy consumption.

Embodied energy payback time

The embodied energy payback time (EEPBT) (year) is the ratio of the embodied energy E_{em} (kWh/m^2), which is the amout of energy required to produce the material in its product form, to the amount of energy obtained per year from the product E_{out} (kWh/m^2/year).

Embodied energy E_{em} for a PV system can be expressed:

$$E_{em} = E_p + E_s + E_f + E_t + E_{BOS} \tag{7}$$

where E_p [kWh] is the embodied energy required for the purification and processing of silicon, E_s – the embodied energy of silicon ingot slicing, E_f [kWh] – the embodied energy for PV module fabrication, E_t [kWh] – the energy to transport PV modules from factory to installation site, and E_{BOS} [kWh]– the embodied energy for components such as support structure, inverter, and electrical wirings.

If we substitute in the eq. (7), the typical values for the silicon monocrystalline PV module as given in [39, 40]: $E_p = 666$ kWh/m^2, $E_s = 120$ kWh/m^2, $E_f = 190$ kWh/m^2, and $E_{BOS} = 358$ kWh/m^2 the embodied energy for our BIPV system of 1020 Wp can be calculated:

$$E_{em} = 1334 \text{ kWh/m}^2 \times 17 \text{ modules} \times 0.514 \text{ m}^2 = 11656.5 \text{ kWh}$$

The embodied energy payback time, the amount of energy obtained per year from the system, and embodied energy payback time, for horizontal, optimally inclined, and vertical BIPV system of 1020 Wp, are given in tab. 3.

Table 3. The embodied energy, the amount of energy obtained per year from system, and embodied energy payback time for horizontal, optimally inclined, and vertical BIPV system of 1020 Wp

Orientation of a BIPV module	E_{em} [kWh]	E_{out} [kWh/year]	EEPBT [year]
Horizontal	11656.5	986.9	10.3
Optimally inclined	11656.5	1069	10.9
Vertical	11656.5	746.7	15.6

Conclusions

The main objective of this study was to compare the performances of horizontal, vertical, and optimally inclined monocrystalline PV modules (ISF-60/12) in real meteorological conditions in city of Nis, Serbia. Our results have shown that in year 2013, the optimally-inclined module generated 62.8 kWh of electrical energy. The horizontal module produced 58.1 kWh, and the vertical module oriented-toward-south generated 43.8 kWh. Obviously, the optimally-inclined module generated the maximum energy output, the output from the horizontal module was 7.5% lower, while the output from the vertical solar module was lower by 31.1%.

Annually, the vertical solar module had the highest value of efficiency (10.9%), followed by the horizontal solar module (10.6%), while the efficiency of the optimally inclined solar module was the lowest (10.2%). The horizontally oriented module had a very stable behavior with small changes of efficiency during the day (both in the winter and in the summer) and with close correlation to the STC predicted efficiency. The reason was that in winter months the ambient temperature and solar irradiance intensity were low and in summer months ambient temperature and solar irradiance incident to the modules surface were high. The efficiency of the optimally inclined module was equal or higher than STC in a winter day while more than 30% lower in a hot summer day, due to the intense heating of the solar cells and high ambient temperature.The vertical solar module had high daily changes of efficiency both in the winter and in the summer. These changes of efficiency of vertical solar module had completely different behavior in different seasons. During the winter, the efficiency decreased during the day (from approximately 17% in the morning and evening to 11% at the noon). Contrary, in the summer day, the efficiency of the vertically-oriented module increased during the day (from approx. 8% in the morning to high 13% in the afternoon). This was because in winter months the ambient temperature was low and solar irradiance intensity high, but in summer months, the ambient temperatures were high and solar irradiance incident to the modules surface was low. Annually, the vertical solar module had the highest value of PR (0.93), followed by the horizontal solar module (0.91) and the optimally-inclined solar module had the lowest PR (0.86). Annually, the horizontal solar module had the highest value of FF (67.7), followed by the vertical solar module (66.6), and finally optimally inclined solar module (63.6). The EEPBT for a horizontal, optimally-inclined and vertical BIPV system of 1020 Wp would be 11.8, 10.9, and 15.6 years, respectively.

The results of this study can be used in modern architecture for practical applications of solar modules as facade and roof elements of residential and other buildings in Serbia. The obtained data could be useful as guidelines in application of solar modules in other countries with a similar climate.

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