Original scientific papers UDK 620.91:523.9
doi: 10.7251/COMEN1502087M

INVESTIGATION OF ENERGY EFFICIENCY OF POLYCRYSTALLINE SILICON SOLAR MODULES IN RELATION TO THEIR GEOGRAPHICAL ORIENTATION AND TILT ANGLE

Dragoljub Mirjanić[1,], Siniša Maksimović[2], Darko Divnić[1], Tomislav Pavlović[3], Lana Pantić[3], Dragana Milosavljević[3]*

[1]Academy of Sciences and Arts of the Republic of Srpska, Bana Lazarevića 1, 78 000 Banja Luka, Republic of Srpska
[2] Elektroprenos BiH, Operational area of Banja Luka, Republic of Srpska
[3] University of Niš, Faculty of Sciences and Mathematics, Višegradska 33, 18 000 Niš, Serbia

Abstract: Investigation of the polycrystalline solar modules energy efficiency in relation to their tilt angle and geographical orientation in the real meteorological conditions are presented in this paper. The experimental system comprises five polycrystalline silicon modules, with single power 50 Wp, three of which are placed vertically and oriented towards the East, South and West, respectively, the fourth is horizontal, while the fifth is oriented toward the South at the angle of 33º (optimally inclined solar module). The measurement period was from 01 August to 01 December, 2014. The optimally inclined solar module generated the most of total monthly energy for all four months. The most of total monthly energy was generated in August, by the optimally inclined solar module (6.07 kWh), horizontal solar module (5.69 kWh), the vertical solar module oriented toward the East (2.42 kWh) and the vertical solar module oriented toward the West (2.52 kWh), respectively. Energy efficiency of optimally inclined solar module for the entire measurement period was 14.27%, 11.41% for the horizontal, 10.37% for the South, 5.79% for the East and 5.23% for the West module. The obtained results can be used in modern architecture, for the application of the solar modules as roof and façade elements.

Keywords: polycrystalline solar modules, orientation of solar modules, energy efficiency.

1. INTRODUCTION

PV modules energy efficiency was found to depend on the physical characteristics of the solar modules and climatic conditions in which the modules are placed. Under ambient working conditions, the energy efficiency differs from the one obtained by the controlled laboratory conditions measurements [1−10]. Therefore, the goal of this paper is to investigate the influence of solar radiation intensity, temperature and wind speed on the polycrystalline crystal silicon modules energy efficiency, differently oriented and with different tilt angles, all under ambient working conditions.

2. EXPERIMENT

The experiment was performed in the Solar Energy Laboratory, at the Academy of Sciences and Arts of the Republic of Srpska in Banja Luka (Bosnia and Herzegovina), from 01 August to 01 December, 2014. The experimental system is composed of 5 polycrystalline solar modules with 50 Wp of single power and the surface of 0,407 m2, attached to the roof steel structure (Figure 1). The orientation of the solar modules is: Module 1 – vertical oriented toward the East, Module 2 – vertical oriented toward the South, Module 3 – vertical oriented toward the West, Module 4 – horizontal, Module 5 – oriented toward the South at an angle of 33° (optimally inclined solar module). The optimum annual inclination angle for the fixed solar modules for Banja Luka (Latitude 44°46'0"North, Longitude 17°10'59"East) was calculated by PVGIS software.

I−V characteristics of the solar modules as well as the maximal power *Pmpp*, short circuit current *Isc*, open circuit voltage *Voc* were measured by I−V analyzer PV-KLA (Ingenieurbüro Mencke & Tegtmeye, Germany), while the meteorological parameters (solar radiation intensity, ambient temperature, wind speed) were measured by the wireless

* Corresponding author: mirjanicd@gmail.com

meteorological weather station Davis Vantage Pro 2 (USA).

In order to compare the measured characteristics of differently oriented solar modules, in real meteorological conditions, measuring was performed subsequently for each solar module, in the shortest possible time delay.

I−V characteristics of the solar modules as well as the maximal power *Pmpp*, short circuit current *Isc*, open circuit voltage *Voc* were measured by I−V analyzer PV-KLA (Ingenieurbüro Mencke & Tegtmeye, Germany), while the meteorological parameters (solar radiation intensity, ambient temperature, wind speed) were measured by the wireless meteorological weather station Davis Vantage Pro 2 (USA).

For this type of measuring a computer controlled device SolarUsbSW (MetteringSolutions, BiH) enables connection and synchronization of measurement cycles. Also, SolarControlM computer software (MetteringSolutions, BiH), which controls this device automatically, monitors the conditions, reliability, synchronization, control, data and archiving of all measuring from all modules, as well as sending notifications of the measuring system interruption.

The logical diagram of the automatic measuring system is presented in Figure 3.

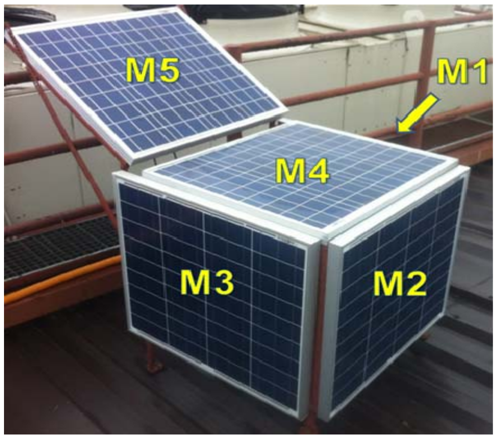

Figure 1.Experimental system (SolarBox) with five differently oriented solar modules

Figure 2. A device for automatic control of measuring SolarUsbSW

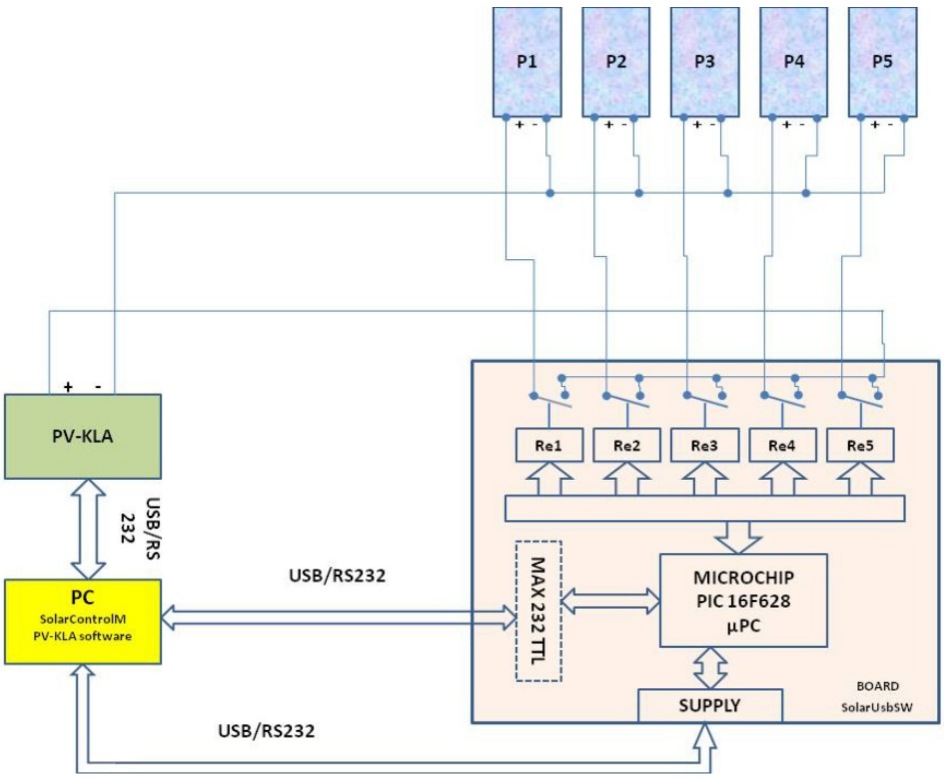

Figure 3. Logical diagram of the automatic measuring system

3. RESULTS AND DISCUSSION

The change of solar radiation intensity falling on a square meter of the horizontal surface on 29 August, 2014, is presented in Figure 4. The maximum value of 716 W/m2 was measured at 1:00 pm.

The change in measured power *Pmpp* for five differently oriented solar modules on 29 August 2014 is shown in Figure 5. The maximal power for Module 5 was measured at 1:00 pm (42.2 W), for Module 1 the maximal power was measured at 8:45 am (33.5 W), for Module 4 maximal power was measured at 1:00 pm (34.7 W), for Module 3 maximal power was measured at 5:15 pm (30.7 W) and for Module 2 maximal power was measured at 1:00 pm (28.83 W).

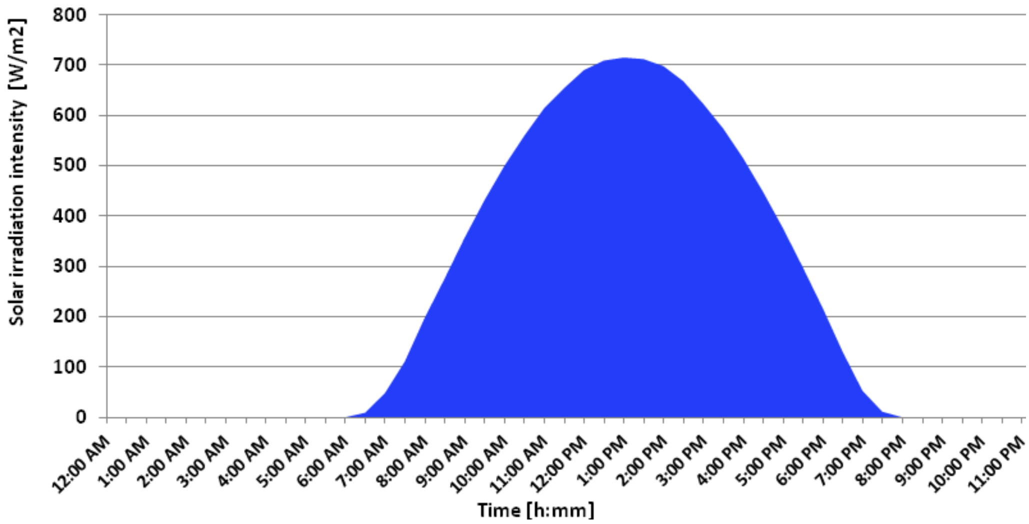

Figure 4. The change of solar radiation intensity falling on a square meter of horizontal surface on 29 August, 2014

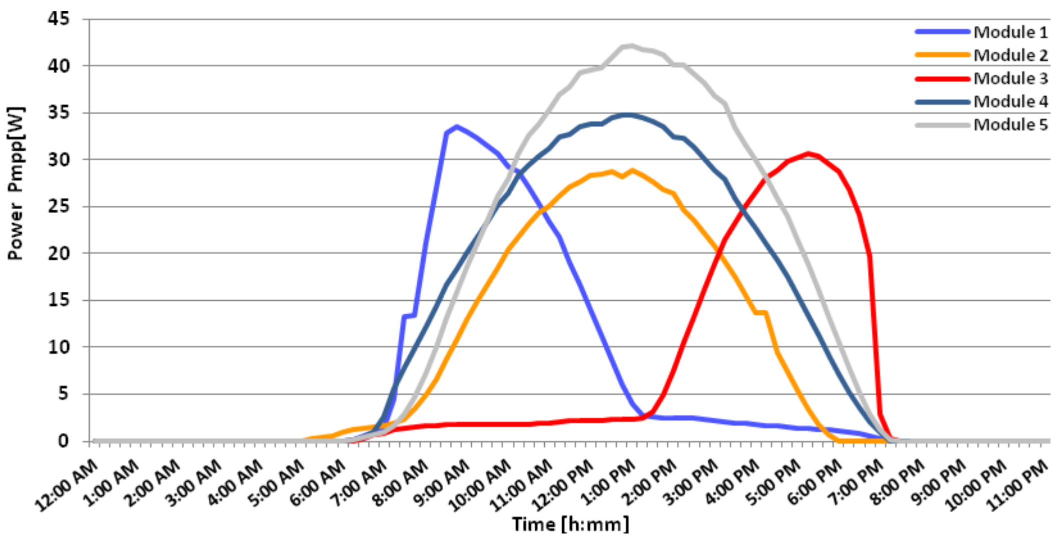

Figure 5. The change in measured power Pmpp for five differently oriented solar modules on 29 August 2014

Further on, the changes of meteorological parameters (solar radiation intensity, ambient temperature, wind speed) will be presented and their influence on energy efficiency of solar modules will be discussed.

The change of solar radiation intensity falling on a square meter of horizontal surface from 01 August to 01 December, 2014 is presented in Figure 6. The highest value of the solar radiation intensity of 845 W/m^2 was measured on 17 August, 2014 at 12:00 pm.

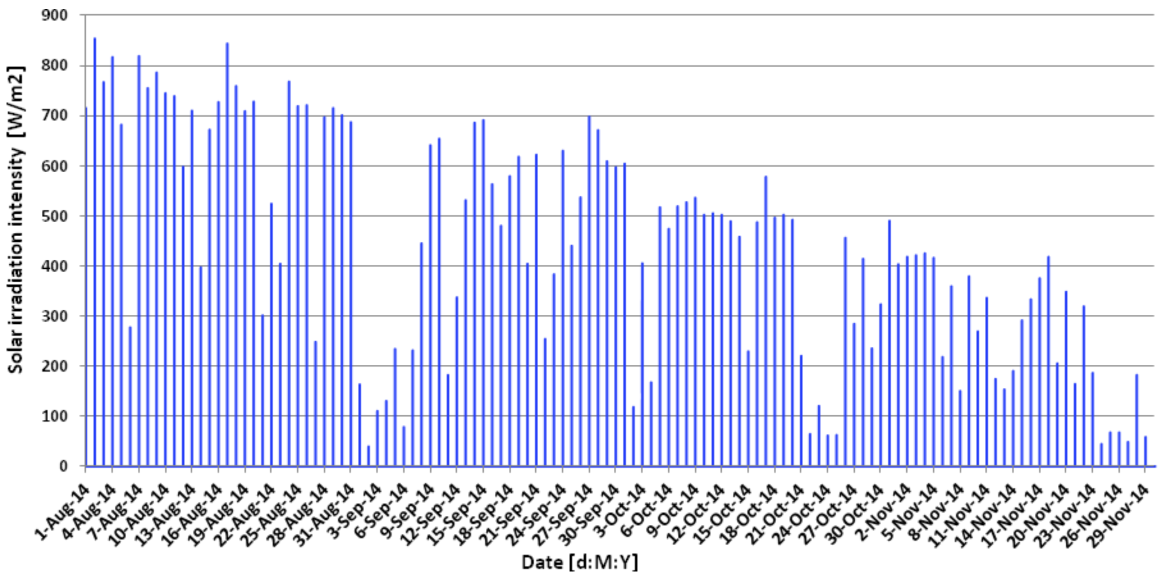

Figure 6. The change of solar radiation intensity falling on a square meter of horizontal surface from 01 August to 01 December, 2014

The change of the ambient temperature from August to November, 2014 is presented in Figure 7. The ambient temperature varied from the highest value of 36.2 °C measured on 9 August, 2014 at 3:30 pm, to the lowest value of -0.3 °C measured on 22 November, 2014 at 5:00 am. The average ambient temperature for the measurement period was 15.7 °C.

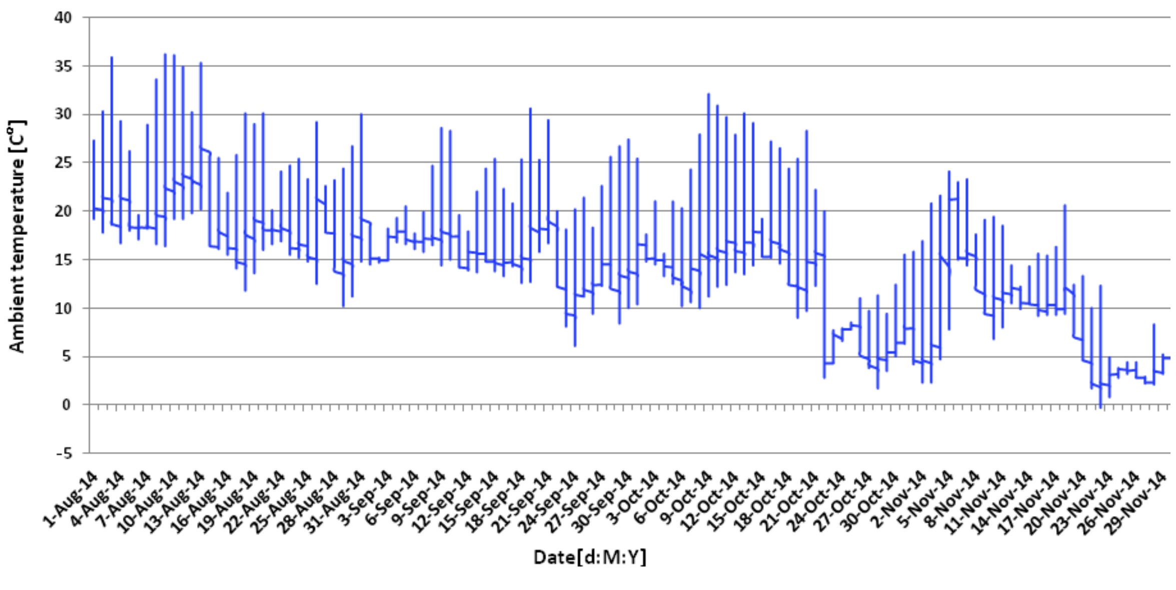

Figure 7. The change of ambient temperature from August to November, 2014

The change of the wind speed from 01 August to 01 December, 2014 is presented in Figure 8. The highest value of wind speed was measured on 06 November, 2014 at 1:00 am, and was 6.3 m/s, while the average wind speed for the measurement period was 0.36 m/s.

The total monthly solar energy falling on a square meter of horizontal surface (Figure 9) ranges from 120.7 kWh/m2 in August to 29.7 kWh/m^2 in November. The total solar energy reaching a square meter of horizontal surface, for the whole measurement period, is 270.5 kWh/m^2.

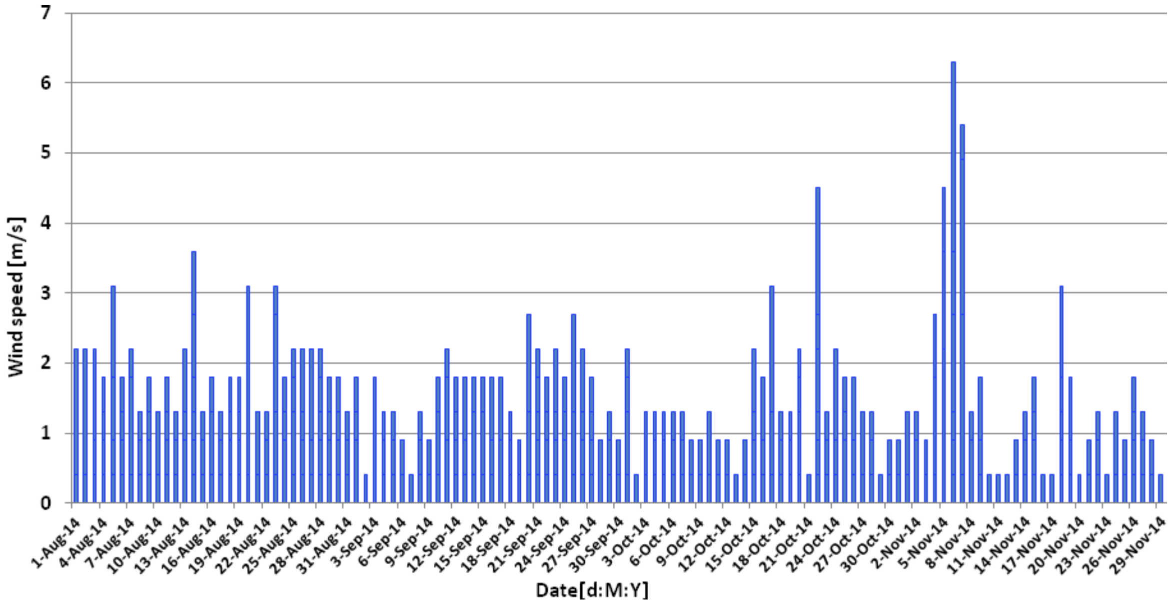

Figure 8. The change of the wind speed from 01 August to 01 December 2014

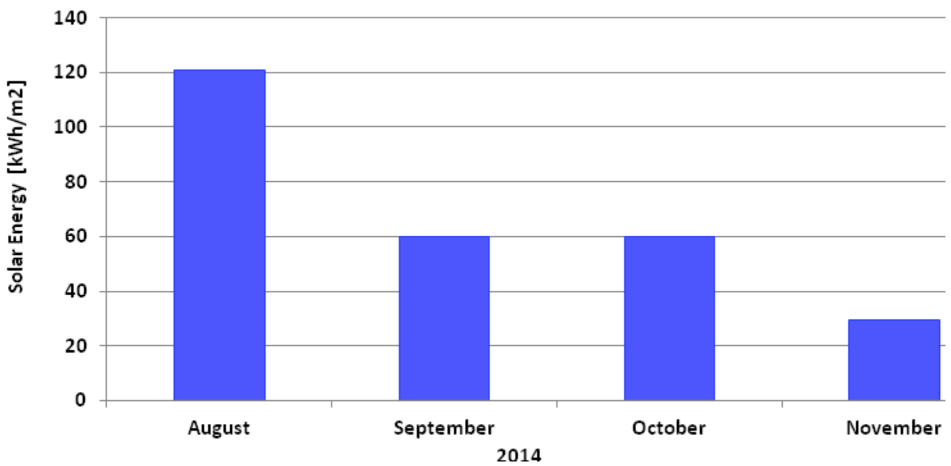

Figure 9. Total monthly solar energy falling on a square meter of horizontal surface from 01 August to 01 December 2014

The daily change of average measured powers Pmpp for all solar modules throughout the measurement period is presented in Figure 10. The maximal average power was 22.28 W for the optimally inclined solar module.

Total monthly electrical energy generated by each solar module for the period 01 August to 01 December 2014, is presented in Figure 11. One can see that the optimally inclined solar module generated the most of total monthly energy for all four months. The most of total monthly energy was generated by the optimally inclined solar module in August (6.07 kWh) while the lowest was generated in November (2.27 kWh). The horizontal solar module generated the most of total monthly energy in August (5.69 kWh) and the lowest in November (1.34 kWh). The Module 2 generated the most of total monthly energy in October (3.45 kWh) while the lowest in November (2.25 kWh). Module 1 and Module 3 generated the most of total monthly energy in August (2.42 kWh and 2.52 kWh, respectively), and the lowest in November (0.90 kWh and 0.65 kWh, respectively).

The total generated energy of each module, for a 4-month measurement period during the fall 2014, is shown in Figure 12. Module 5 generated 15.70 kWh, Module 4 − 12.58 kWh, Module 2 − 11.45 kWh, Module 3 − 5.77 kWh and Module 1 generated 6.37 kWh.

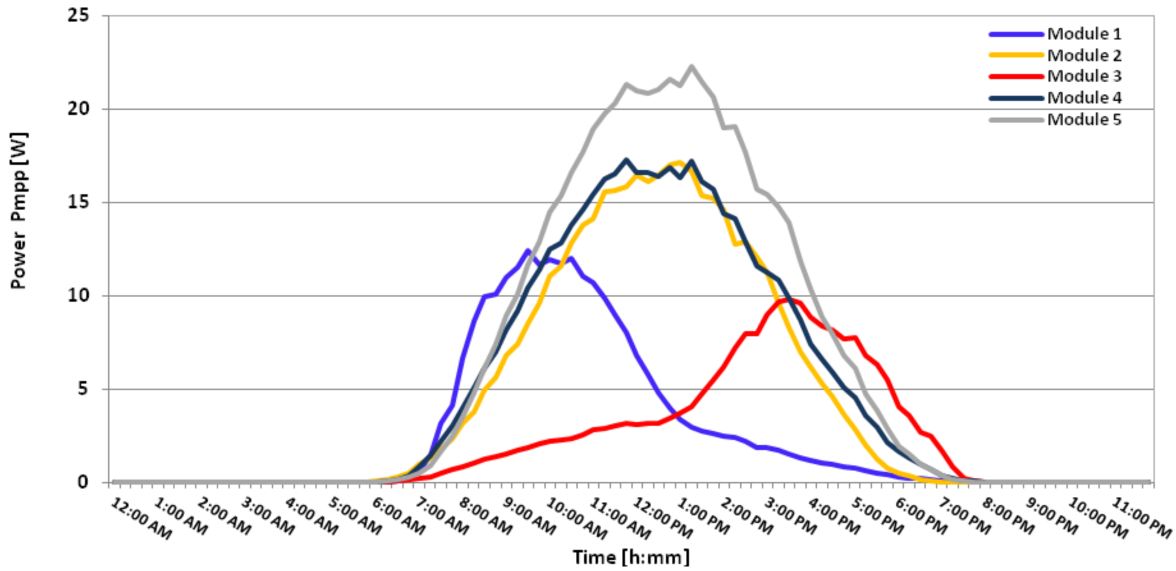

Figure 10. Daily change of average measured powers Pmpp of all solar modules throughout the measurement period

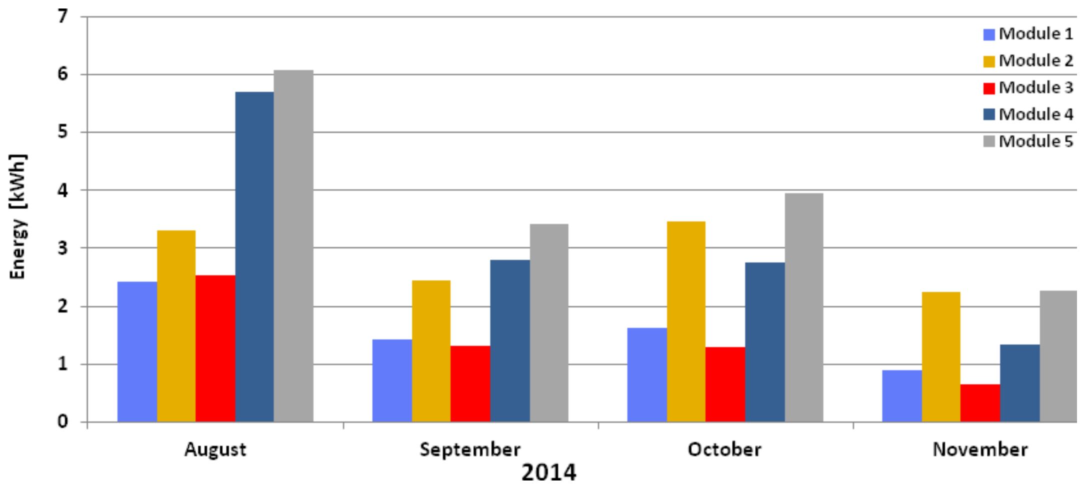

Figure 11. Total monthly electrical energy generated by each solar module for the period 01 August to 01 December 2014

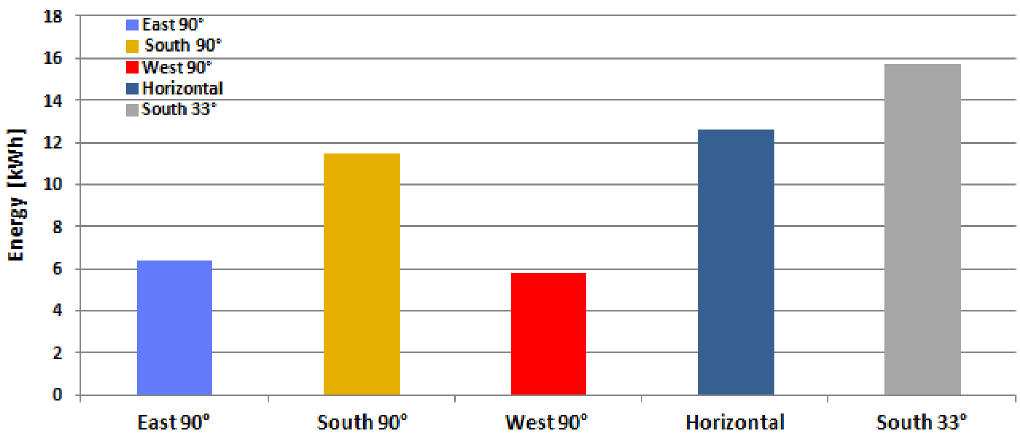

Figure 12. Graphical presentation of total generated energy for each module during the measurement period

The change of the monthly energy efficiency of each solar module during the measurement period is presented in Figure 13.

The average energy efficiency for each solar module for the entire measurement period is shown in Figure 14. Average energy efficiency of optimally inclined solar module for the entire measurement period was 14.27%, the average energy efficiency of horizontal solar module was 11.41% and the average energy efficiency of Module 2 was 10.37%. The average energy efficiency for Modules 1 and 3 was 5.79% and 5.23%, respectively.

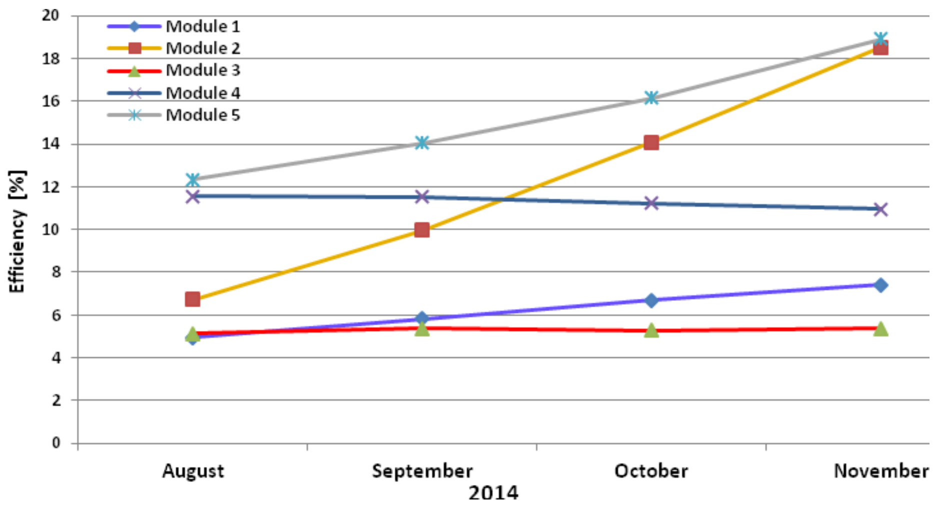

Figure13. The change of monthly energy efficiency of each solar module

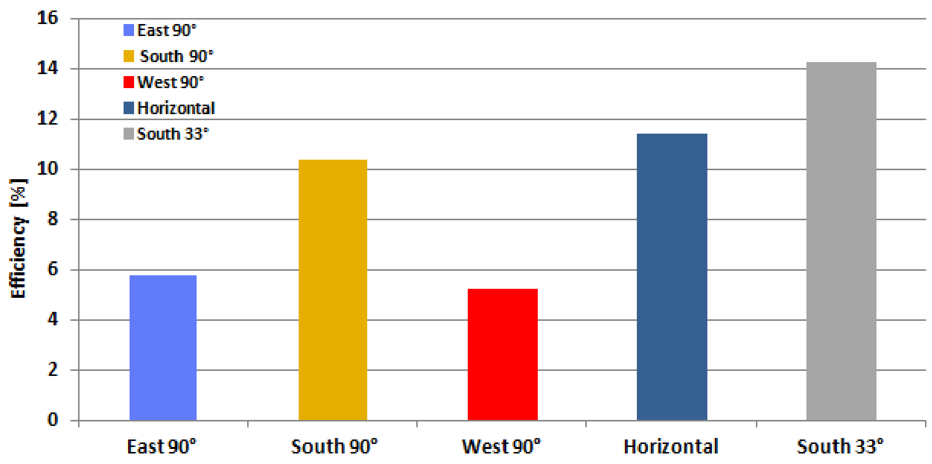

Figure 14. Average energy efficiency for each solar module for the entire measurement period

4. CONCLUSION

Based on the presented results for the period from 01 August to 01 December, 2014, it can be concluded that:

− The highest value of solar radiation intensity of 845 W/m^2 was measured on 17 August, 2014 at 12:00 pm.

− The ambient temperature varied during the measurement period in the interval from -0.3°C to 36.2°C, while the average ambient temperature for the measurement period was 15.7 °C.

− The highest value of wind speed was measured on 06 November 2014 and amounts to 6.3 m/s, while the average wind speed for the measurement period was 6.3 m/s.

− The total monthly solar energy falling on a square meter of the horizontal surface ranges from 120.7 kW/m^2 in August to 29.7 kW/m^2 in November.

− The maximal average power for the measurement period was 22.28 W for the optimally inclined solar module.

− The optimally inclined solar module generated the most of total monthly energy for all four months while total generated energy for a 4-month measurement period was 15.70 kWh.

− The average energy efficiency of optimally inclined solar module for the entire measurement period was 14.27%, 11.41% for Module 4, 10.37% for Module 2, 5.79% for Module 1 and 5.23% for Module 3, respectively.

− Further research could provide guidelines and recommendations for the use of different types of PV panels in architecture, both as roof and façade elements of the buildings.

5. ACKNOWLEDGMENT

This paper was done with the financial support of the project 19/6-020/961-102-1/11 approved by the Ministry of Science and Technology of the Republic of Srpska.

6. REFERENCES

[1] T. Pavlović, D. Milosavljević, D. Mirjanić, *Renewable Energy Sources*, Academy of Sciences and Arts of the Republic of Srpska, Banja Luka 2013, 1−364.

[2] A. Luque, S. Hegedus, *Handbook of Photovoltaic Science and Engineering*, Second Edition, 2011, John Wiley & Sons, 1−1166.

[3] T. Pavlović, Z. Pavlović, L. Pantić, Lj. Kostić, *Determining optimum tilt angles and orientations of photovoltaic panels in Nis, Serbia,* Contemporary Materials, Vol. I−2 (2010) 151−156.

[4] T. Markvart, L. Castafier, *Fundamentals of Photovoltaic Modules and Their Applications*, 2003, Elsevier Science Ltd., Oxford, UK,

[5] D. Lj. Mirjanić, S. Maksimović, D. Divnić, *The study of energy efficiency of monocrystalline silicon modules*, Contemporary Materials, Vol. V−2 (2013) 117−124.

[6] E. Skoplaki, J. A. Palyvos, *On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations*, Solar Energy, Vol. 83 (2009) 614–624.

[7] G. Xydis, *On the energetic capacity factor of a wind e solar power generation system*, Journal of Cleaner Production (2012) 1−9.

[8] T. Pavlović, D. Milosavljević, D. Mirjanić, L. Pantić, I. Radonjić, D. Piršl, *Assessments and perspectives of PV solar power engineering in the Republic of Srpska (Bosnia and Herzegovina)*, Renewable and Sustainable Energy Reviews, Vol. 18 (2013) 119–133.

[9] S. Pless, M. Deru, P. Torcellini, S. Hayter, *Procedure for Measuring and Reporting the Performance of Photovoltaic Systems in Buildings*, 2005, National Renewable Energy Laboratory, Colorado, USA.

[10] H. Haberlin, *Photovoltaics: system design and practice*, 2012, John Wiley & Sons, UK.

ИСПИТИВАЊЕ ЕНЕРГЕТСКЕ ЕФИКАСНОСТИ СОЛАРНИХ МОДУЛА ОД ПОЛИКРИСТАЛНОГ СИЛИЦИЈУМА У ЗАВИСНОСТИ ОД ЊИХОВЕ ГЕОГРАФСКЕ ОРИЈЕНТАЦИЈЕ И УГЛА НАГИБА

Сажетак: У раду су дати резултати испитивања енергетске ефикасности соларних модула од поликристалног силицијума у зависности од њихове географске оријентације и угла нагиба у реалним климатским условима. Експериментални систем се састоји од пет соларних модула појединачне снаге 50 Wp, од којих су три постављена вертикално према истоку, југу и западу респективно, четврти је хоризонталан, а пети је постављен под углом од 33° према југу. Оптимално постављен соларни модул је генерисао највише електричне енергије од 1. августа до 1. децембра 2014. године. У августу је оптимално оријентисан соларни модул произвео 6.07 kWh, хоризонтални 5.69 kWh, вертикално оријентисан према истоку 2.42 kWh и вертикални према западу 2.52 kWh електричне енергије. Енергетска ефикасност оптимално оријентисаног соларног модула за цијели период мјерења је 14.27%, хоризонталног 11.41%, вертикалног према југу 10.37%, вертикалног према истоку 5.79% и вертикалног према западу 5.23%. Добијени резултати могу се користити у модерној архитектури, за примјену соларних модула као кровних и фасадних елемената.

Кључне ријечи: енергетска ефикасност, поликристални соларни модули, географска оријентација.