

COMPARISON OF THE ANNUAL POWER BALANCE OF PHOTOVOLTAIC MODULES

POREĐENJE GODIŠNJEG URAVNOTEŽENJA SNAGE FOTONAPONSKIH MODULA

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ABSTRACT

This article presents the results of a research study focusing on the effect of tilt angle changes on the power balance of photovoltaic (PV) systems. The objective of this study was to determine tilt-angle-induced differences in the power balance of two different types of photovoltaic modules: bifacial and monofacial. A comparison of the power balance results, obtained for the PV modules installed on the roof of a building with tilt angles of 25° and 90°, was made. Ultimately, the simulation of power changes was performed for the modules installed on the roof with different black and white surfaces. The measurement data were collected using the solar invertors FRONIUS IG and the pyranometer CMP 11. The results obtained indicate that the PV system integrated into the building's façade had a better power balance than the PV system installed on the building's roof in the period from October to January. The power of the bifacial PV modules considered was found to be greater than that of the monofacial PV modules considered. The energy production of bifacial modules proved greatly dependent on the roof surface reflection coefficient.

Key words: PV system, tilt angle, PV construction, year.

REZIME

U radu su prikazani rezultati istraživanja usredsređeni na prepoznavanje uticaja promena ugla nagiba na uravnoteženje snage fotonaponskih (PV) sistema. Cilj je bio ustanovljavanje razlika u promeni snage za dve različite vrste fotonaponskih modula - dvofazni i monofacijalni. Upoređeni su rezultati uravnoteženosti snage za PV module instalisane na krovu sa uglom nagiba 25° i 90°. Na kraju su simulirane promene snage modula instaliranih na krovu sa različitim crnim i belim površinama. Iz dobijenih rezultata jasno je da je PV sistem integrisan u fasadu zgrade imao bolju uravnoteženost snage od sistema na krovu od oktobra do januara. Snaga dvofacijalnih PV modula bila je veća od snage monofacijalnih. Proizvodnja energije dvofaznih modula veoma zavisi od koeficijenta refleksije krovne površine.

Ključne reči: PV sistem, ugao nagiba, konstrukcija PV, godina.

INTRODUCTION

As the most cost-effective of all renewable power generation technologies, solar power generation technologies are important for providing a major share of the clean and renewable energy needed in the future. With increased sustainability, solar power generation will become competitive to fossil-fuel power generation within the next decade. Solar power generation has proven to be one of the most attractive options for electrical energy production in grid-connected and distributed modes (Reddy *et al.*, 2013). Photovoltaic (PV) cells are devices which directly convert solar energy into electrical energy (Chander *et al.*, 2015). The possibilities of photovoltaic system application have been argued by both Slovak (Cviklovič and Olejár, (2013), Olejár *et al.*, (2015)) and international researchers (Čorba *et al.*, (2009) and Milićević *et al.*, (2012)). The power, efficiency and quantity of the electricity generated by photovoltaic systems depend on a number of external factors: the intensity of solar radiation, ambient temperature, wind speed, the temperature of PV modules, the reflectivity of PV module surfaces and the reflectivity of the roof and/or wall surfaces where PV modules are installed (Kafui *et al.*, 2018). However, a great many internal factors, which also exert a major effect on photovoltaic electricity generation, must be taken into account: the material and construction of PV modules, the angle of construction orientation to the cardinal directions, the tilt angle of PV

modules, etc. This article deals with the effect of tilt angle changes on the power balance of PV systems. The parameters of two PV systems with tilt angles of 25° and 90° were examined in the present study. The purpose of this paper is to compare the annual power balance of bifacial monocrystalline PV modules with a tilt angle of 25° and monofacial (classic) monocrystalline PV modules with the same tilt angle installed on the façade (with a tilt angle of 90°) or roof (with a tilt angle of 25°) of a building.

MATERIAL AND METHOD

The measurements were done using one of the biggest solar power stations in the Czech Republic, which is installed on the roof of the Faculty of Education, Masaryk University (Fig. 1). This photovoltaic power plant has a peak performance of 40 kWp (Sládek, 2006; Sládek, 2008). The whole area of the photovoltaic system covers 337.2 m². The photovoltaic power plant started operating in January 2006 and was oriented SW. The PV modules had to be installed with a tilt angle of 25°, which is not optimal from a theoretical perspective (Libra (2009) as the ideal tilt angle for this location would be 35°, because the building itself is an important architectural monument. The photovoltaic system is divided into three sections. The first section consists of 48 monofacial monocrystalline panels SI 72-110. The technical parameters of the SOLARTEC SI 72-110 PV module are presented in Table 1. The total power output of the PV system section is 5kWp. The first part of the PV system is

integrated in the façade of the building (see Fig. 1). The second section of the PV system, consisting of 288 identical monofacial monocrystalline modules, was located on the building's roof. The total power output of the second section is 30 kWp. The third section of the PV system, with a total power of 5 kWp, is equipped with the bifacial monocrystalline PV modules SBI2G 72-90BR (the technical parameters of these models are presented in the second part of Tab. 1). The bifacial modules (Fig. 2) produce solar power on both sides of the panel.



Fig. 1. PV system on the Faculty of Education, Masaryk University

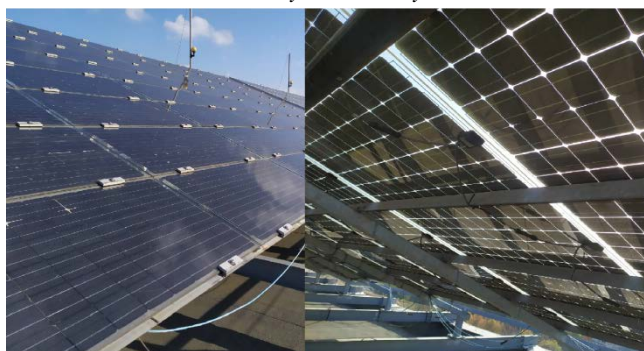


Fig. 2 Bifacial PV modules SBI2G 72-90BR-MC

Tab. 1 Technical parameters of the monofacial and bifacial monocrystalline PV modules SOLARTEC SI 72-110 (Solartec, 2019) and SBI2G 72-90BR-MC

SOLARTEC SI 72-110	
Solar cells	72 pcs, monocrystalline 4" Si
Maximum power peak P_{max}	110 W_p
Voltage at P_{max}	17.4 V
Open-circuit voltage	21.6 V
Short-circuit current	6.76 A
Rated current P_{max}	6.32 A
Maximal system voltage	760 V
SBI2G 72-90BR-MC	
Solar cells	72 pcs, monocrystalline 4" Si
Maximum power peak P_{max}	90 W_p
Voltage at P_{max}	35.2 V
Open-circuit voltage	43.1 V
Short-circuit current	2.73 A
Rated current P_{max}	2.56 A
Maximal system voltage	600 V

For converting the DC voltage supplied by the photovoltaic cells to an AC voltage of 230 V/50 Hz, a total of 5 FRONIUS IG40 voltage converters and 3 FRONIUS IG60HV voltage converters were used (the efficiency of these converters is 94.3 %). The whole photovoltaic system is connected, via the main switchboard, to the internal power network of the faculty, which includes three buildings. This makes it possible to supply the electricity generated to the grid.

The following parameters were observed in the experiments: the intensity of solar radiation in $W.m^{-2}$ and the power of the PV

systems in W. Differences in the power values recorded were computed and expressed in W and % (Tab. 2, Tab. 3 and Tab. 4).

The solar radiation was measured with the pyranometer Kipp&Zonen CMP11. The CMP11 pyranometer uses a 32-junction thermopile detector and provides an expected output of (0 – 20) mV based on a sensitivity of $7-14 VW^{-1}.m^{-2}$. The power of the PV system was detected using the datalogger FRONIUS.

RESULTS AND DISCUSSION

The power of the PV modules considered was compared over the course of one year. As large experimental data sets were collated, the data obtained were selected for processing and presented using model days for every calendar month. The average values of weather parameters for a particular month were used for the model day representing that month. These days were without extreme changes in cloudiness. The time range from 9 a.m. to 4 p.m., i.e. when the solar radiation is strongest, was selected for the power evaluation of the PV systems on a particular model day. The power values of the PV systems considered, measured according to different installation locations and tilt angles, were compared in the following manner: the power of the monocrystalline PV modules – BIPV, installed on the building's façade with a tilt angle of 90° , was compared with the power of the same PV module installed on the building's roof with a tilt angle of 25° . Subsequently, the power values of the bifacial PV modules with a tilt angle of 25° and the monofacial PV modules with the same tilt angle were processed and compared. As seen in Tab. 2, the monocrystalline bifacial PV modules were found to have the average power balance higher by 7.6 % than that of the classic monocrystalline PV modules during the calendar year. This can be accounted for by the fact that monocrystalline bifacial glazing PV modules can also use reflected solar radiation from the roof surface onto which they are installed. The smallest difference in the PV module power values (1.4 %) was computed for March. Percentage differences higher than 10 % were computed for the period from August to December. The PV solar power stations on the roof of the Faculty of Education is placed on the black asphalt board IPA, so the main advantage of bifacial photovoltaic modules was not used to the maximum extent. The ideal surface for the installation of bifacial PV modules should have the maximum reflectivity coefficient, i.e. albedo. For the purpose of comparison, a simulation was performed with higher albedo values (namely white surface placed under the bifacial PV modules) in May.

Tab. 2 Comparison of the bifacial monocrystalline PV module with a tilt angle of 25° (P_1) and the monofacial monocrystalline PV module with a tilt angle of 25° (P_2)

Month	P_1 [W]	P_2 [W]	ΔP [W]	ΔP [%]
January	1483.03	1520.76	-37.72	2.48
February	101.38	97.62	3.75	3.71
March	173.42	170.89	2.42	1.4
April	3092.15	3003.35	88.8	2.8
May	3429.46	3238.37	190.5	5.55
June	3775.38	3603.6	171.78	4.51
July	3271.51	3084.77	186.74	5.7
August	3103.93	2762.39	368.28	11.86
September	3084.69	2762.39	322.37	10.43
October	1950.79	1685.58	265.2	13.59
November	1374.26	1165.5	208.76	15.19
December	1448.41	1238	208.83	14.48

The results of this simulation are shown in Figure 3. A comparison between the monocrystalline PV and monocrystalline BIPV modules considered indicates that the monocrystalline PV modules with a 25° tilt angle had higher power values in the period from February to September (Tab. 3). The average difference in the PV system power values was 52.1 % (in the same period).

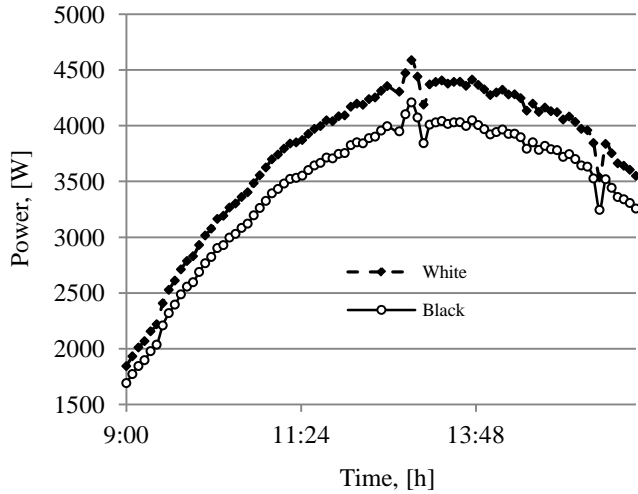


Fig. 3 Simulation of a white surface under the bifacial PV modules

Tab. 3 Comparison of the monofacial monocrystalline PV module with a tilt angle of 25° (P₂) and the monocrystalline PV module located on the building's façade (P₃)

Month	P ₂ [W]	P ₃ [W]	ΔP [W]	ΔP [%]
January	1520.76	2602.43	-1081.67	43.01
February	97.62	21.02	76.6	78.46
March	170.89	60.43	110.55	64.63
April	3003.35	2310.49	692.86	23.06
May	3238.37	1494.79	1741.17	53.77
June	3603.6	1366.14	2237.46	62.08
July	3084.77	1403.5	1681.26	54.5
August	2762.39	1427.66	1307.98	47.81
September	2762.39	1864.43	897.88	32.5
October	1685.58	2237.85	-552.26	25.67
November	1165.5	1825.85	-660.35	36.16
December	1238	2278.82	-1029.82	45.51

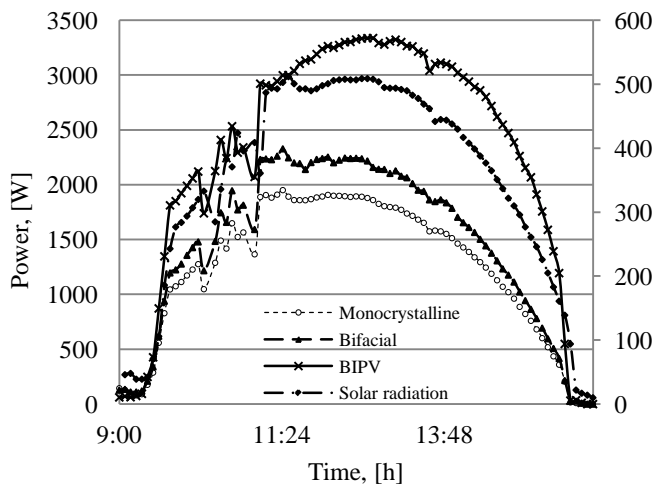


Fig. 4 Power of the PV modules considered in December

Tab. 4 Comparison of the bifacial monocrystalline PV module with a tilt angle of 25° (P₁) and the monocrystalline PV module located on the building's façade (P₃)

Month	P ₁ [W]	P ₃ [W]	ΔP [W]	ΔP [%]
January	1483.03	2602.43	-1119.4	43.01
February	101.38	21.02	80.36	79.18
March	173.42	60.43	112.98	65.15
April	3092.15	2310.49	781.66	25.27
May	3429.46	1494.79	1931.68	56.34
June	3775.38	1366.14	2409.24	63.81
July	3271.51	1403.5	1868.01	57.09
August	3103.93	1427.66	1676.27	54.01
September	3084.69	1864.43	1220.26	39.55
October	1950.79	2237.85	-287.05	12.82
November	1374.26	1825.85	-451.58	24.73
December	1448.41	2278.82	-820.98	36.28

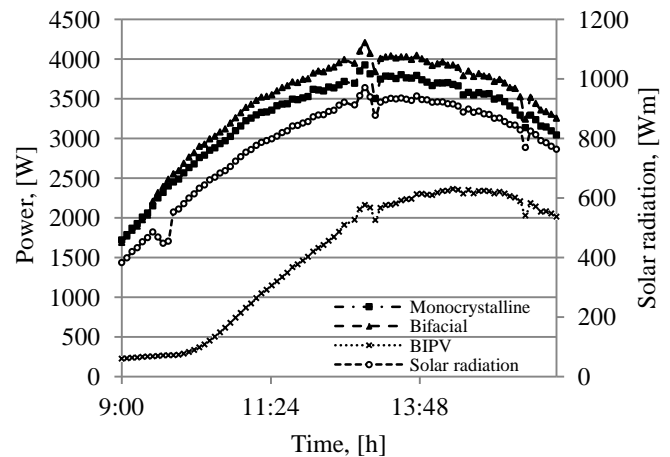


Fig. 5 Power of the PV modules considered in May

The incident angle θ of direct solar radiation affects the solar radiation intensity on the solar module. It depends on the tilt angle and varies according to the season: the incident angle is smaller in the winter and larger in the summer due to the position of the Sun in the sky (Kaddoura et al., 2016). Larger tilt angles of PV modules are better in the winter (Libra, 2009).

The power of the monocrystalline BIPV module was found to be higher in the period from October to January, with an average power balance difference of 37.6 %. Time relations of power and solar radiation intensity were established for the different types of PV modules considered on the model day in December (Fig. 4). A comparison between the bifacial PV module and the monofacial PV module installed on the building's façade (Tab. 4) indicates that the monocrystalline bifacial PV modules with a 25° tilt angle had a better power balance in the period from February to September, with an average percentage difference of 55.05 %. The BIPV module had higher power values in the period from October to January and a percentage difference of 29.21 %. Figure 5 shows the power of individual PV systems in the period under consideration for the model day in May. The intensity of solar radiation depends on both the weather data (namely ambient temperature and wind speed) and the incident angle θ (Fig. 6).

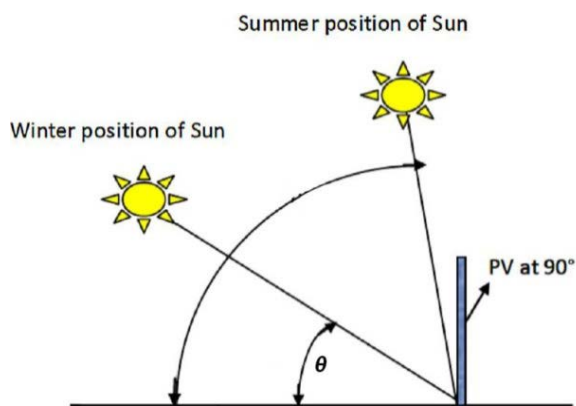


Fig. 6 Summer and winter position of the Sun (Jovanovic et al., 2017)

The annual power efficiency of the BIPV module was reported in the literature by Jovanovic et al., (2017). They measured the energy production of BIPV modules at tilt angles of 30° and 90° in Podgorica (Montenegro). The results obtained by Jovanovic et al., (2017) confirm that BIPV modules with a tilt angle of 90° produce more electricity than PV modules with a smaller tilt angle (30°) in the period from October to January (Fig. 7). In the present study, the PV power plant at the Faculty of Education, Masaryk University, had a tilt angle of 25°.

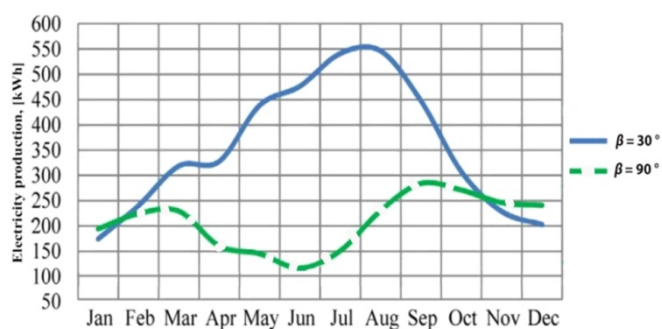


Fig. 7 Electricity production of PV modules with tilt angles of 30° and 90° in Podgorica, Montenegro (Jovanovic et al., 2017)

CONCLUSION

The results obtained indicate that the position of the Sun and the tilt angle of photovoltaic modules exert a significant effect on their power. The data measurements were performed using the photovoltaic system installed on the building of the Faculty of Education, Masaryk University, in Brno. Bifacial monocrystalline photovoltaic modules were found to have a positive power balance throughout the year, but their performance is conditioned by many operational factors. The most important external operational factors are weather conditions (particularly the intensity of solar radiation) and the reflectivity of the surface placed under PV modules. The surfaces with minimal reflectivity (the black IPA) can positively affect the performance of the PV system when using the bifacial technology (the average annual performance of PV systems increased by 7.6 % in this study). Furthermore, the PV system integrated into the building's façade (with a PV module tilt angle of 90°) produced more energy under normal operating conditions (with a better power balance and a difference of approximately 30 %) than the PV modules placed on the building's roof with a tilt angle of 25°. The PV module power measurements were performed in the period from October to January, when solar radiation is minimal. The results obtained are in good agreement with the results of Jovanovic et al., (2017).

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