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Study of Photovoltaic Systems' Performances with Different Module Types

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Abstract. The purpose of the work is to study and compare the performance of photovoltaic (PV) generators built with different types of panels and operating in real weather conditions. The paper reports the results from an experimental and theoretical study of systems with PV modules manufactured according to different technologies and using different materials. The experiment was carried out at a research platform for PV systems developed by the authors, built and located at an experimental site near the Technical University of Sofia. Based on the obtained results, comparisons are made between the different PV generators for the same operating conditions. The comparison between the theoretical and the experimental results demonstrates a good level of overlap.

Introduction

Comparing the performances of PV modules produced by different technologies is an important problem and has been the subject of much research [1], [2], [3]. The data given by the producers is not sufficient to evaluate the performance of a PV generator composed of modules of the same type. This is due mainly to the fact that real operating conditions vary and can be significantly different from the Standard Test Conditions (STC) reproduced in the facility. In order to obtain a real picture of the performance of different PV technologies, data has to be collected over considerable periods of time from PV generators placed next to each other, exposed to exactly the same conditions [1], [2]. On the other hand, validation of the mathematical models could facilitate and reduce the uncertainty in PV plant energy estimation and planning [4], [5], [6]. The aim of this paper is to compare the performance of PV installations made up of modules with different technologies, operating under the same conditions. Mathematical models of type "input - output" for all PV generators are developed based on the experimental data.

Test facility presentation

The PV generators used for the tests comprise modules of different technologies and materials: monocrystalline silicon (mSi), polycrystalline silicon (pSi), microcrystalline silicon (μcSi), copper indium-gallium selenide (CIGS) and cadmium telluride (CdTe) [3]. All PV installations are assembled in a manner that allows for the similar peak power at STC: around 1200Wp. Each photovoltaic array is connected to the grid through a single-phase inverter of type SB1200. The PV panels are mounted on tracker systems which allow operation in tracking mode or at identical predefined fixed orientation for all systems under test (see Fig.1). The test facility is located in the city of Sofia, Bulgaria, with coordinates 42°39'16"N, 23°21'17"E.

Some more information about the tested PV generators is given in Table 1. The data for power generation, (currents, voltages, powers etc.) and for the weather conditions (temperature, solar radiation and wind speed) is collected via a monitoring and data acquisition system based on the Sunny Webbox data logger. The data recording time interval is 5 min. The data used in this study was collected from the beginning of August 2014 until the end of January 2015.

Table 1. Basic parameters of the studied photovoltaic generators

Module type	mSi	pSi	µcSi	CIGS	CdTe
Installed peak power [Wp]	1200	1200	1280	990	1125
Rated efficiency at STC [%]	14.81	14.63	9.01	11.70	10.42
Array area [m^2]	8.2	8.2	14.2	8.45	10.8

Fig. 2 shows a portion of the collected data (solar radiation in the panel planes, cell temperatures and generated powers) for one day in September 2014. The temperature is measured by sensors attached to the panel surfaces which is assumed equal to the cell temperature.

Fig. 1. Test facility - solar trackers

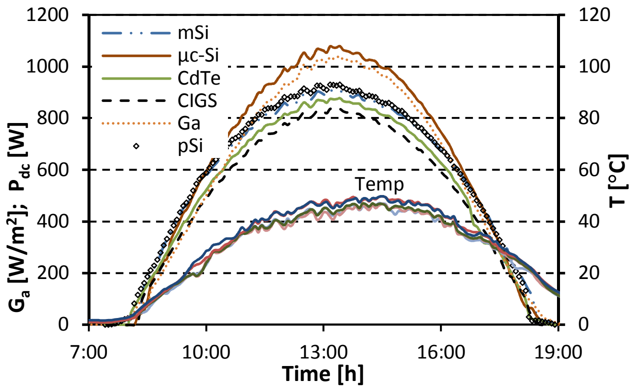

Fig. 2. Experimental results for solar radiation, cells' temperature and power yield for five PV generators

The experimental values of the PV generator efficiency η_{exp} are calculated according to the expression

$$\eta_{exp} = \frac{P_{exp}}{G_a A} \tag{1}$$

where P_{exp} is the measured electrical power on the output of the PV generator, G_a is the measured solar radiation in the panels' plane, A – PV array total area.

Theoretical study and comparisons

The model presented by Durisch in [4] is used for the theoretical estimation of PV generator efficiency η_{pv} at maximum power point (MPP) at given operating and meteorological conditions,

$$\eta_{pv} = p\left[q\frac{G_a}{G_{ar}} + \left(\frac{G_a}{G_{ar}}\right)^m\right] \times \left[1 + r\frac{T_c}{T_{cr}} + s\frac{AM}{AM_0} + \left(\frac{AM}{AM_0}\right)^u\right] \tag{2}$$

where G_a is the solar radiation in the panels' plane, T_c – cell temperature, AM – air mass density, the reference conditions are G_{ar} =1000W/m^2, T_{cr} =25ºC and AM_0=1.5; p, q, m, r, s and u are coefficients specific to each PV module technology.

The determination of the values of these coefficients is a very important task which allows the calculation of the efficiency for given conditions. From the collected data, one day from each month was chosen for coefficient determination – six days in total. The selected days were subject to various meteorological conditions and therefore the operation points of the PV generators are different and cover a wide range of solar radiations and a wide range of temperatures.

The values of measured electrical power of the PV generators are converted to powers at standard value of the irradiance G_{ar}=1000W/m^2 using the expression

$$P_1 = P_{exp}\frac{G_{ar}}{G_a}. \tag{3}$$

This is done for values of G_a between 850 and 1100W/m^2 as the uncertainty of measured data in this range is relatively small. The obtained values of the power are plotted versus the temperature values as shown in Fig. 3. For each set of points was created a fitting line with corresponding equation in the form

$$y=ax+b, \tag{4}$$

where y stands for the power P_1 and x stands for the temperature T_c.

The slope of the line indicates the temperature dependence of the produced power and subsequently of the efficiency of each PV generator. This holds true under the assumption that the efficiency is constant at a given temperature in the range of the irradiation values between 850 and 1100W/m^2, as it is shown in previous works [1], [2].

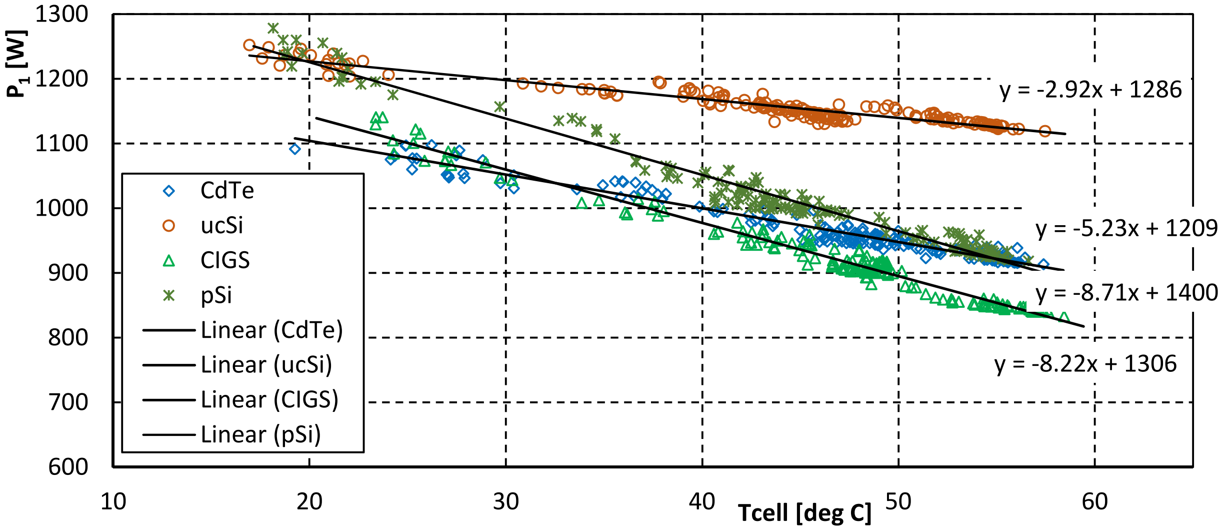

Fig. 3. Measured power transformed to standard irradiation of 1000W/m^2 versus cell temperature

Now the temperature coefficient r is calculated from the equation

$$r = a\frac{25}{b}. \tag{5}$$

With temperature coefficients already known, the other parameters in Eq. (1) have been identified for each of the PV generators using consecutive fitting procedures for minimizing the mean squared error between the calculated and measured electric power P_{exp}. The obtained values of the coefficients for all PV systems are listed in Table 2.

Table 2. Coefficients' values for the mathematical models of PV generators

Coefficient/Module type	mSi	pSi	µcSi	CIGS	CdTe
p	23.1	23.5	12.1	20.4	15.1
q	-0.281	-0.291	-0.248	-0.251	-0.252
m	0.155	0.132	0.180	0.271	0.171
r	-0.150	-0.149	-0.054	-0.152	-0.112
s	-0.981	-0.983	-1.081	-0.979	-0.991
u	0.985	0.982	1.012	0.987	0.979

The temperature coefficient of the CIGS modules is the largest and that of the microcrystalline silicon modules - the smallest. The temperature dependence of the efficiency of CIGS modules is slightly bigger than that of the crystalline silicon modules. The CdTe modules have a temperature coefficient between those of µcSi and crystalline silicon modules.

Fig. 4 shows the fit between the plotted theoretical efficiency curve and the experimental efficiency points transformed to a standard temperature of 25°C in dependence with the irradiation for the CdTe system. Fig. 5 provides a comparison between the calculated efficiency curves at 25°C using the determined parameters for all five PV generators. The differences between the overall efficiency values are clearly visible. The calculated efficiencies correspond to those given by the manufacturers with the exception of the CIGS system. The calculated efficiency of the CIGS generator at STC is around 13% while in the datasheet it is 11.7% (see Table 1). This difference is likely due to the non-degraded state of the modules – they are still in the first year of their exploitation. As can be seen in Fig. 5, there are also some differences between the forms of the efficiency curves.

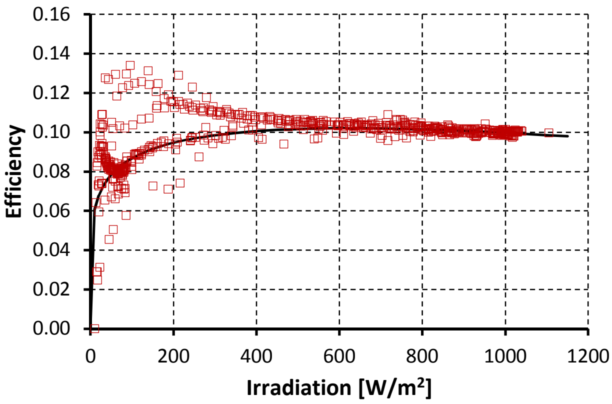

Fig. 4. Experimental efficiency transformed to 25°C and simulated efficiency curve for CdTe system

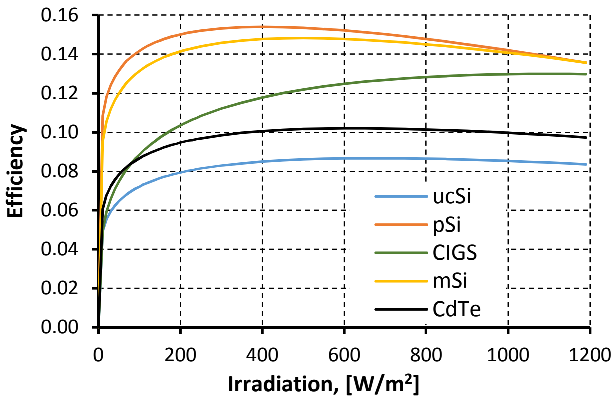

Fig. 5. Calculated efficiency curves at 25°C for five studied PV generators

Fig. 6 and Fig. 7 show a three-dimensional plot of the efficiency for two of the studied PV generators – with CIGS and with μcSi panels. The difference in the temperature dependence of the efficiency can be clearly seen.

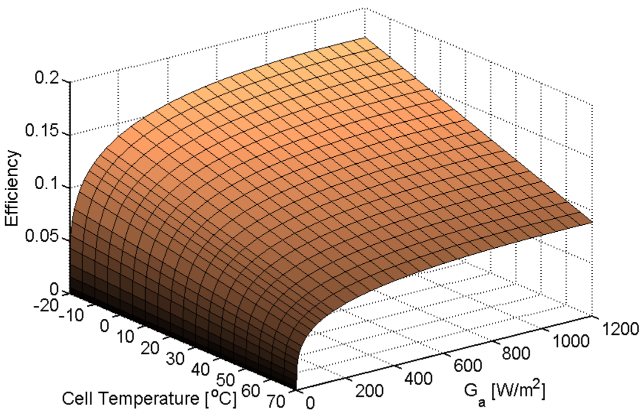

Fig. 6. Simulated efficiency surface for PV generator with CIGS panels

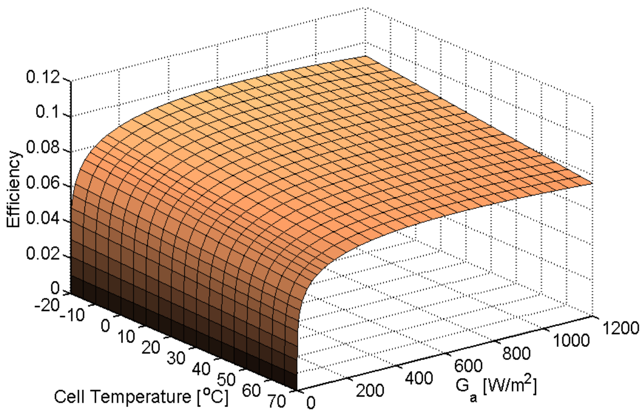

Fig. 7. Simulated efficiency surface for PV generator with μcSi panels

The adopted mathematical model was tested by calculating the generated power and energy of the studied PV generators. The measured solar radiation and cell temperature were used as inputs. The calculations were performed for different days from the six-month period. Comparisons of experimental and simulation results for two days with very different meteorological conditions are presented on Fig. 8 and Fig. 9. The calculated PV power using the recorded values for cell temperature and solar radiation shows a good match with the measured PV power.

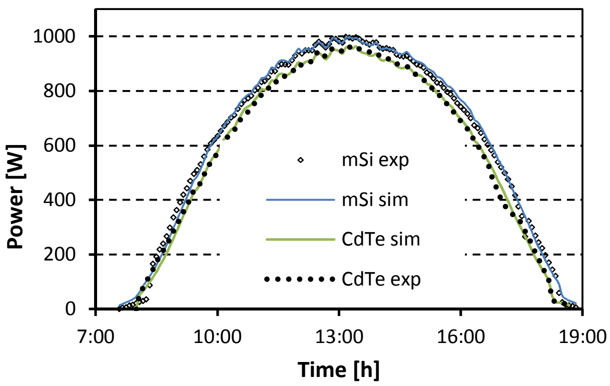

Fig. 8. Measured and calculated PV power of mSi and CdTe generators for 10.08.2014

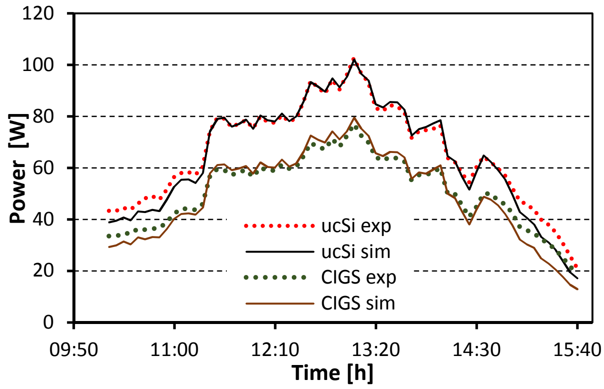

Fig. 9. Measured and simulated PV power of μcSi and CIGS generators for 14.12.2014

Using the experimental data, real PV performance parameters have been calculated for the generators subject to the test. In table 3 results are presented for three cases with different positions of the PV systems and different meteorological conditions. It can be seen that in different weather conditions different PV systems perform best (see the bolded numbers in the table).

Table 3. Comparison between experimental and theoretical performance of PV generators

Module type	mSi	pSi	μcSi	CIGS	CdTe
10.08.2014 South-West, fixed angle 30°, average cell temperature 28.3 °C					
Experimental productivity E_e [kWh/kWp]	6.178	6.275	**6.945**	6.547	6.423
Theoretical productivity E_t [kWh/kWp]	6.087	6.189	**6.820**	6.546	6.246
Difference $(E_e - E_t)/ E_e$ [%]	1.47	1.37	1.80	0.02	2.76
Experimental productivity [kWh/m^2]	0.832	0.832	0.564	0.685	0.605
Experimental daily efficiency E_{el}/E_{sol} [%]	12.05	**12.33**	8.20	10.30	9.00
14.12.2014 South, fixed angle 30°, average cell temperature 2.7 °C					
Experimental productivity [kWh/kWp]	**0.344**	0.326	0.284	0.281	0.269
Theoretical productivity [kWh/kWp]	**0.344**	0.330	0.278	0.276	0.265
Difference $(E_e - E_t)/ E_e$ [%]	0.00	-1.23	2.11	1.78	1.49
Experimental productivity [kWh/m^2]	**0.050**	0.048	0.026	0.033	0.028
Experimental daily efficiency E_{el}/E_{sol} [%]	14.47	**15.35**	7.30	9.49	9.03
12.01.2015 Solar tracking, average cell temperature 10.5°C					
Experimental productivity [kWh/kWp]	3.208	3.186	2.937	**3.326**	2.921
Theoretical productivity [kWh/kWp]	3.263	3.257	2.978	**3.344**	2.974
Difference $(E_e - E_t)/ E_e$ [%]	-1.71	-2.23	-1.40	-0.54	-1.81
Experimental productivity [kWh/m^2]	**0.469**	0.466	0.265	0.390	0.304
Experimental daily efficiency E_{el}/E_{sol} [%]	14.94	**15.16**	8.49	12.59	9.87

Fig. 10 shows comparison between the performance ratios PR of the PV generators in different weather conditions. The values are calculated from the experimental data for six different days in the studied time period of 6 months according to the equation

$$PR = \frac{E_e / P_{STC}}{H_S / G_{aref}}, \tag{6}$$

where E_e is total produced energy for the period in kWh, P_{STC} - rated power at STC in kW, H_S - total solar energy in the collector plane in kWh/m^2 and G_{aref} - reference irradiation for STC in kW/m^2.

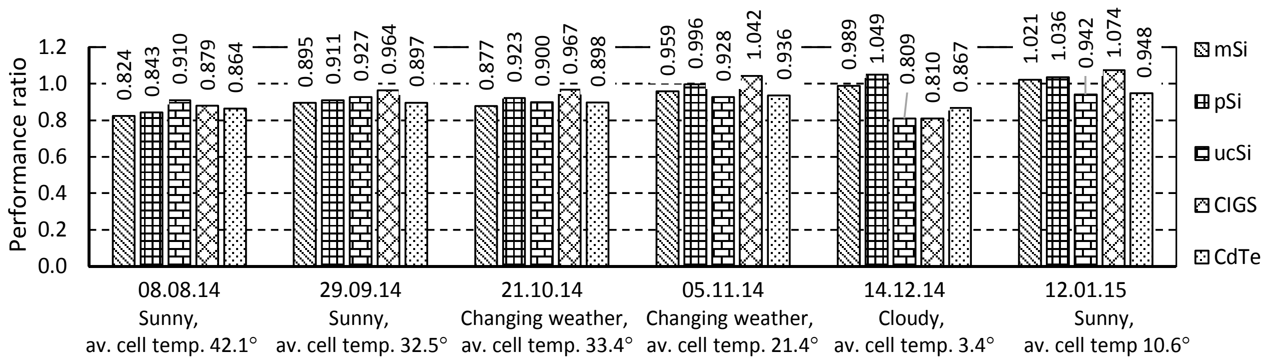

Fig. 10. Comparison of the performance ratios of studied PV generators under different conditions

Under cold winter conditions the productivity of the CIGS modules visibly improves and even outperforms these of the crystalline silicon modules. The PR values over 1 are due to the low operating temperatures - lower than the STC temperature of 25ºC.

Conclusion and discussion

The paper shows results from an experimental and theoretical study of PV generators composed of modules produced by different materials and technologies. All generators are installed at the same site in Sofia, Bulgaria and are subject to the same conditions. The experimental results are compared to those from a theoretical model and the resulting mean square error is under 3%. As expected, the crystalline Si modules have the highest efficiency, followed by CIGS, CdTe and μcSi modules. On hot sunny days the energy yield per kWp (kWh/kWp) of the μcSi PV system is higher that the yield of the other technologies. On cold sunny days the CIGS system performs best due to the temperature dependence of its efficiency. Surprisingly, under low-radiation conditions the crystalline silicon modules give best results but this is probably due to the very low temperatures during the day when values were measured. The system with CdTe modules ranks average for all measured performance values. Based on these results, it is not possible to decide which module technology is the higher performing one because each displays certain advantages under specific weather conditions. Operating under certain meteorological conditions, the thin-film modules (CdTe, CIGS and μcSi) are competitive to the already well-established crystalline silicon technologies.

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