

Determining energy production of CdTe photovoltaic system

Abstract. This paper presents a method for determining energy production of Cadmium-Telluride photovoltaic system, which has a different working performance than the most used Silicon photovoltaic systems. The main difference is sensitivity to the temperature and the solar irradiance. The CdTe cells are less sensitive to the temperature and in contrast to the Si Cells they have a higher efficiency at lower irradiance.

Streszczenie. W artykule przedstawiono metodę wyznania energii wytworzonej przez system paneli fotowoltaicznych z tellurku kadmu (CdTe), różniących się od klasycznych krzemowych. Głównymi różnicami między nimi jest wrażliwość na zmiany temperatury i nasłonecznienia, gdzie system CdTe wykazuje mniejszą wrażliwość na temperatury natomiast Si wyższą sprawność przy niskim nasłonecznieniu. (System fotowoltaiczny CdTe – wyznaczenie wytwarzanej energii).

Keywords: photovoltaic module, energy production, annual energy yield, Cadmium-Telluride.

Słowa kluczowe: panel fotowoltaiczny, wytwarzanie energii, roczna wydajność energetyczna, tellurek kadmu.

Introduction

One of the most important parameters in the recovery of investment costs of photovoltaic (PV) power plant is the energy yield, which tells how much electrical energy the plant will produce in a given period. The energy yield generally depends on four elements: the components of the plant, the plant location, the weather and the losses.

The basic components of the photovoltaic systems are photovoltaic modules, inverters and cables. For better energy yield the components with high quality have to be chosen, because the PV power plant will operate for many decades. Besides the guarantee of the modules operation the classifying to the classes and subclasses has an important role as well. The entire branch of the modules will work as the worst module. For more accurate calculation of energy yield, it is important to know the PV module performance [1, 2]. It is also important to be careful with the choice of inverters and cables. By the inverters the maximum power, the maximum permissible voltage, the maximum permissible current and the conversion efficiency have important role. By the cables a comparison between the losses and price has to be done. In practice, the cables are determined to have the voltage drop less than 1% [3].

For better energy yield the fixed PV plant must be oriented to the south with the tilt that is closest to the optimal tilt for a given area. The optimal tilt fixed power plant for Slovenia is around 30° [3]. Even greater energy yield could be achieved with sun tracking systems. With the optimal regulation, the annual energy yield will increase for approximately 40% to 50% [4]. It must be ensured that the PV modules are not shadowed in any season. By setting up the modules on the roof, the sufficient cooling of modules must be ensured, which means that the air bridge between the roof and the modules has to be built.

The energy yield is strongly associated with the weather because the electrical energy is produced directly from the solar energy. The exact weather cannot be predicted in the form of equations and it can be calculated only for clear days [5] or be predicted from long-term averages, minimums and maximums. The weather data can be obtained from various databases. The most accurate data can be obtained from the meteorological data stations, of course, if they are in the vicinity of the plant location. Otherwise the interpolation of several remote meteorological data stations or a satellite images has to be used. Of the last two the satellite pictures are more accurate, but generally they give average values between two meridians and two parallels. The data from various databases can vary up to 10%.

Energy yield of PV system is, beside the meteorological data, strongly connected with the losses. As a source of the energy, the solar radiation on a horizontal surface of the earth will be taken. After that the losses follow in subsequent order:

- losses due to the inclination of the surface (to the south orientations are generally increments);
- losses due to reflection on the glass of module;
- losses due to glass contamination (dust, snow);
- losses due to temperature;
- losses due to irradiance;
- losses resulting from the conversion of solar energy into electricity;
- losses due to mismatch of the power of modules;
- losses due to mismatch of the characteristics of modules in branches;
- losses in the wires on the DC side;
- losses resulting from the conversion of DC voltage into AC voltage;
- losses in the wires on AC sides.

All these losses can be divided into two groups. The first group contains losses, which can be accurately determined at any time. These are losses due to the inclination of the surface, losses due to reflection on glass modules, losses due to temperature, losses due to irradiance, losses in the conversion of solar energy into electrical energy, losses in the wires on the DC side, losses in the conversion of DC voltage into AC voltage and losses in the wires on AC side. The second group contains losses that cannot be accurately measured, but can be based on experience and determined assumptions. These are losses due to contamination of glass, loss of power due to the mismatch of modules and loss due to mismatch of connected modules in the branches. When calculating the energy yield the maximum values of losses have to be considered.

Table 1. The nominal data for module FS-277

Nominal power ($\pm 5\%$)	P_{mpp} [W]	77,5
Voltage at maximum-Power	V_{mpp} [V]	69,9
Current at maximum-Power	I_{mpp} [A]	1,11
Open Circuit Voltage	V_{oc} [V]	90,5
Short Circuit Current	I_{sc} [A]	1,22
Temperature Coefficient of Current	α_i [%/°C]	0,04
Temperature Coefficient of Voltage	β_v [%/°C]	-0,25
Normal Operation Cell Temperature	$T_{c,NOCT}$ [°C]	45

PV module performance

In order to prescribe the PV module performance, the test under real conditions must be made. Based on the results of the test, the coefficients of equation (1) [1] are determined. The CdTe PV module type FS-277 of the First

Solar manufacturer was tested under real conditions by using instrument HT IV-400. The nominal data of tested PV module are given in table 1.

Figures 1 and 2 show the results of the PV module test. Figure 3 shows the ambient and module temperature measured at the time of the test.

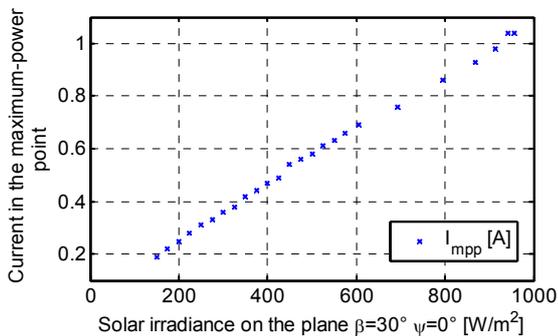


Fig.1. The current in the maximum-power point

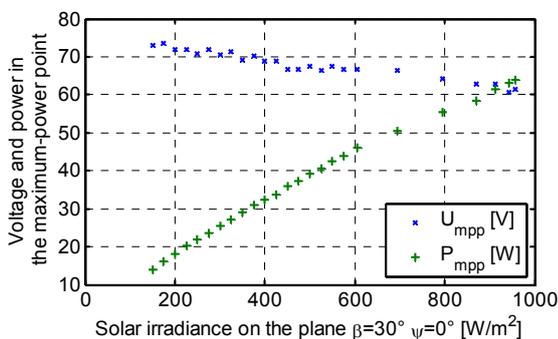


Fig.2. The voltage and the power in the maximum-power point

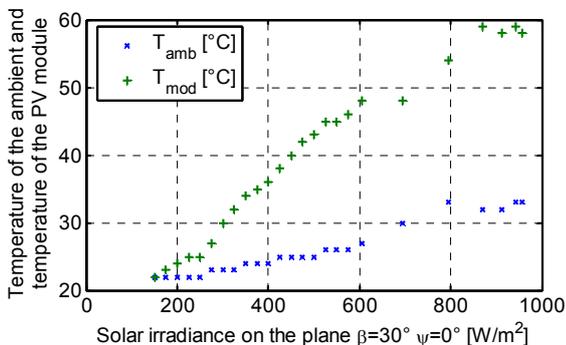


Fig.3. The temperature of the ambient and the PV module

The equation (1) has been adjusted according to the results of test. The coefficients of equation (1) are presented in table 2.

$$P_m = P_{STC} \cdot \left(C_0 \cdot \frac{G_c}{G_{STC}} + C_1 \cdot \left(\frac{G_c}{G_{STC}} \right)^2 \right) \cdot \left(1 + \alpha_i \cdot (T_c - T_{c,STC}) \right) \cdot \left(1 + C_2 \cdot N_s \cdot \delta_T \cdot \ln \left(\frac{G_c}{G_{STC}} \right) + C_3 \cdot N_s \cdot \left(\delta_T \cdot \ln \left(\frac{G_c}{G_{STC}} \right) \right)^2 + \beta_v \cdot (T_c - T_{c,STC}) \right) \quad (1)$$

where: P_{STC} – nominal power by STC, G_{STC} – irradiance by STC (1000 W/m²), $T_{c,STC}$ – cell temperature by STC (25 °C),

G_c – irradiance on the cell, T_c – cell temperature, N_s – number of cells in series, δ_T – thermal voltage.

Table 2. The coefficients of the equation of the PV module performance

Coefficient	C_0 []	C_1 []	C_2 [1/W]	C_3 [1/W ²]
Value	0,7761	0,1093	-0,1363	-1,032

Figures 4 and 5 show the comparison between the results of the measurements, the equation (1) and the commercial software package for calculating the energy yield of PV systems PVsyst. The relative efficiency is the ratio between the efficiency by the real conditions and efficiency by the standard test conditions (2).

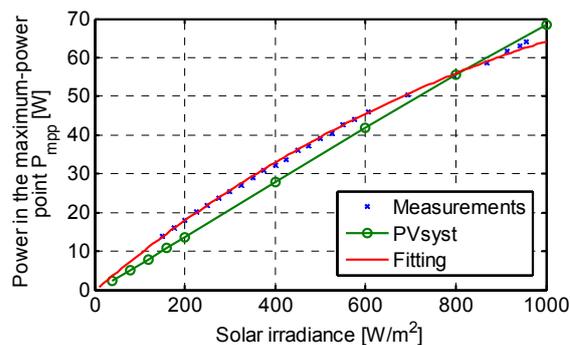


Fig.4. The power in the maximum-power point at the real conditions

$$\eta_{rel} = \frac{P_m}{G_c \cdot A} \cdot \frac{G_{STC} \cdot A}{P_{STC}} \quad (2)$$

where: A – surface area of the PV module. In comparison to silicon PV modules, the CdTe PV modules have higher efficiency at lower solar irradiance. The relative efficiency at lower solar irradiance is even greater than 100%. The reason for a big difference between measured values and values calculated with software PVsyst is in a bad performance model of CdTe module in PVsyst. The relative efficiency of CdTe module calculated with PVsyst is similar to the relative efficiency of silicon modules, where the value of relative efficiency is lower than 100 %.

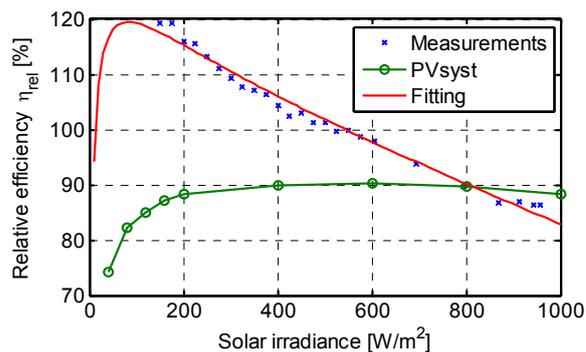


Fig.5. Relative efficiency at the real conditions

Input data

Values of the solar irradiance on the PV cell and the PV cell temperature are also required for calculation of the power of a PV module. Previously mentioned parameters can be obtained from meteorological data stations, global irradiance, diffuse irradiance and ambient temperature. These data are collected for time periods of 15-60 minutes, depending on the meteorological data station. The solar irradiance on the module can be calculated with the following equation [6, 7]:

$$(3) \quad G_c = \left(G_b \cdot \frac{\cos(i)}{\sin(\alpha)} + G_d \cdot \frac{1 + \cos(\beta)}{2} + G_g \cdot \rho \cdot \frac{1 - \cos(\beta)}{2} \right) \cdot \left(1 - b_0 \cdot \left(\frac{1}{\cos(i)} - 1 \right) \right)$$

where: G_b – beam irradiance, G_d – diffusive irradiance, G_g – global irradiance, α – angular height of the sun, β – tilt of the module, ρ – reflective factor of the surrounding area, b_0 – reflective factor of the glass, i – angle of incidence of solar ray. The angular height of the sun can be calculated with the equation (4):

$$(4) \quad \alpha = \arcsin(\sin(L) \cdot \sin(\delta) + \cos(L) \cdot \cos(\delta) \cdot \cos(h))$$

where: L – geographical latitude, δ – declination, h – hour angle. The hour angle can be calculated with equation (5):

$$(5) \quad h = -180^\circ - l + (H_0 + H + H_\Delta) \cdot 15^\circ$$

where: l – geographical longitude, l_0 – time zone, H – time of the day, H_Δ – summer / winter time (-1 / 0). The temperature of the cell can be calculated with the following expression [8]:

$$(6) \quad T_c = (T_{c,NOCT} - T_{amb,NOCT}) \frac{G_c}{G_{NOCT}} + T_{amb}$$

where: $T_{amb,NOCT}$ – temperature of the ambient by NOCT (25 °C), G_{NOCT} – solar irradiance of the ambient by NOCT (800 W/m²).

Calculation of the energy yield

Once the power of a PV module is determined, the power of the whole system can be calculated as well. The power on the AC side can be calculated by using the equation (7).

$$(7) \quad P_{AC} = P_m \cdot n_m \cdot (1 - \varepsilon_{con}) \cdot (1 - \varepsilon_{pow}) \cdot (1 - \varepsilon_{arr}) \cdot (1 - \varepsilon_{ohmDC}) \cdot \eta_{inv} \cdot (1 - \varepsilon_{ohmAC})$$

where: n_m – number of modules, ε_{con} – losses due to contamination, ε_{pow} – losses due to mismatch of the powers, ε_{arr} – losses due to mismatch of the characteristics, ε_{ohmDC} – ohmic losses in wires, η_{inv} – efficiency of the inverter, ε_{ohmAC} – ohmic losses in wires. The energy yield is calculated as integral of the produced power on the AC side, as it is given by the equation (8).

$$(8) \quad W_{AC} = \int P_{AC} \cdot dt = \sum P_{AC} \cdot \Delta t$$

Results

The power of the PV power plant with 3769 modules of the manufacturer First Solar, type FS-277 and 16 inverters of manufacture SMA type STP1700TL is measured. The results of the measured power are obtained by the communication unit Sunny WebBox produced by the SMA. The meteorological data are measured by using sensor unit Sunny SensorBox produced by the SMA. The meteorological and the geographical data are presented in the table 3.

Table 3. Meteorological and geographical data on August 18 2011 at 10:45

Parameter	Symbol	Value
Geographical longitude	L	16,176 °
Time zone	H_0	+1
Summer/winter time (-1/0)	H_Δ	-1
Geographical latitude	L	46,633 °
Global irradiance	G_g	752 W/m ²
Diffuse irradiance	G_d	165 W/m ²
Temperature of module	T_m	48,9 °C
Temperature of ambient	T_{amb}	22,3°C

Table 4 presents measured and calculated results for each inverter and the sum of all inverters in the last row. In the last column, the relative differences between measured and calculated results are presented. These values are between -4,67% and +6,85%. The relative difference between measured and calculated results for all inverters is -0,79%. The reason why the difference among the results occurs lies within the losses, which are different for different systems. The losses, which are taken into account in calculations, are determined on the basis of the usual recommendations given in [9]. These losses are presented in table 5.

Table 4. Comparison of measured and calculated power

n_m	β [°]	φ [°]	P_{me} [W]	P_{ca} [W]	ε [%]
252	8	14	12.003,0	12.525,6	4,35
234	8	14	12.205,0	11.632,6	-4,67
234	8	14	11.631,0	11.632,6	0,01
234	8	14	12.135,0	11.632,6	-4,14
234	8	14	11.649,0	11.632,6	-0,14
234	8	14	12.105,0	11.632,6	-3,90
234	8	14	11.634,0	11.632,6	-0,01
234	8	14	11.496,0	11.632,6	1,19
225	8	-166	10.513,0	10.481,8	-0,30
225	8	-166	10.679,0	10.481,8	-1,85
225	8	-166	10.795,0	10.481,8	-2,90
225	8	-166	10.904,0	10.481,8	-3,87
251	8	-166	11.633,0	11.693,1	0,52
251	8	-166	11.789,0	11.693,1	-0,81
251	8	-166	10.943,0	11.693,1	6,85
226	9	14	11.562,0	11.258,4	-2,63
3769	x	X	183.676,0	182.218,7	-0,79

Figure 6 shows the division of the power for the first inverter.

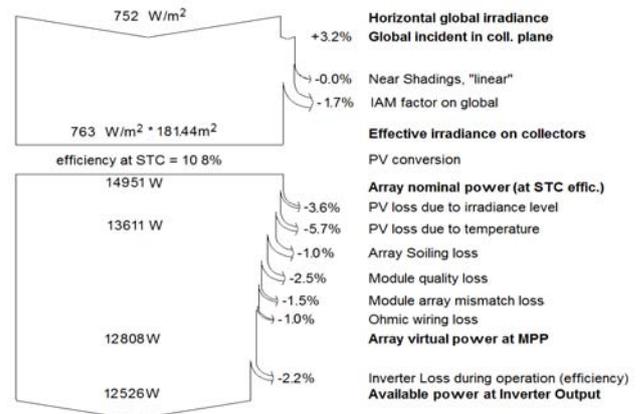


Fig.6. Diagram of the power calculated for the system connected to the first inverter

Table 5. Losses taken into account by calculations

ϵ_{con}	ϵ_{pow}	ϵ_{arr}	ϵ_{ohmDC}	η_{inv}
1%	2,5%	1,5%	1%	97,8%

The analysis of the meteorological data is required in order to calculate the energy yield. In Fig. 7, 8 and 9 are presented meteorological data obtained from meteorological data station Murska Sobota (source: ARSO – Slovenian Environment Agency) and they refer for the last 10 years period of time. All the data are collected in periods of 30 minutes.

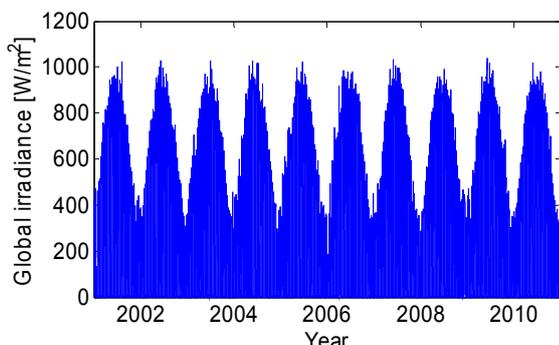


Fig.7. Global irradiance on horizontal plane

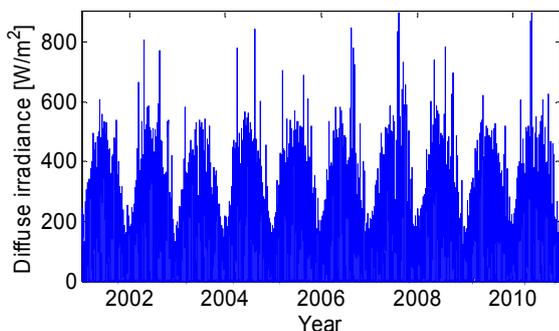


Fig.8. Diffuse irradiance on horizontal plane

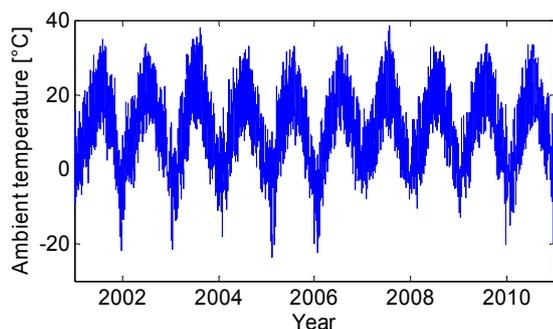


Fig.9. Ambient temperature

On the basis of these data, some statistics are made. The mean value, minimum annual value, maximum value, sum of the worst months and sum of the best months of annual global irradiation on horizontal plane, annual diffuse irradiation on horizontal plane and annual average ambient temperature can be obtained. The results of the previous calculations are presented in table 6. The energy yield of the PV power plant with nominal power of 442,8 kW located nearby the meteorological data station Murska Sobota is calculated for five different conditions. The data of energy yields are presented in table 7. On the basis of the meteorological data from the last 10 years, the value of the

annual energy yield are by annually conditions 491,8·(±0,06) MWh, or in the worst/best case 491,8·(±0,14) MWh by monthly conditions.

Table 6. Meteorological data

	Annual global irradiation [kWh/m ²]	Annual diffuse irradiation [kWh/m ²]	Annual average ambient temperature [C°]
Mean value	1.274,2	605,3	10,49
The worst year (2004)	1.194,9	579,5	11,15
Sum of the worst months	1.078,0	523,1	7,69
The best year (2003)	1.371,9	637,9	9,36
Sum of the best months	1.477,2	701,4	13,14

Table 7. Produced energy in MWh

Mean value	The worst year (2004)	Sum of the worst months	The best year (2003)	Sum of the best months
491,8	464,6	422,4	523,4	562,4

Conclusion

This paper presents a methodology for the determination of energy production of the CdTe photovoltaic system. The energy yield is directly calculated from the meteorological and geographical data with known PV module performance and losses of the system.

The exact value of the future annual energy yield cannot be determined, because of the two main factors. Firstly, no equation, which can reliably describe the future weather, can be obtained. It can only be calculated on the basis of a long-term averages, minimums and maximums. Secondly, some losses cannot be accurately calculated and need to be chosen on the basis of the experiences and recommendations. For more accurate calculation of the energy yield, the PV module characteristics of the particular module have to be known.

REFERENCES

- [1] King D.L., Boyson W.E., Kratochvil J.A., Photovoltaic array performance model, 2004
- [2] Huld T., Gottschalg R., Beyer H.G., Topič M., Mapping the performance of PV modules, effects of module type and data averaging, *Solar Energy*, 84 (2010), 324-338
- [3] Lenardič D., Fotonapetostni sistemi (Photovoltaic systems), instructions, 2009
- [4] Seme S., Štumberger G., A novel prediction algorithm for solar angles using solar radiation and differential evolution for dual-axis sun tracking purposes, *Solar energy*, 85 (2011), 2757-2770
- [5] Seme S., Štumberger G., Voršič J., Maximum efficiency trajectories of a two-axis sun tracking system determined considering tracking system consumption, *IEEE Trans. Power Electron.*, 26 (2011), 1280-1290
- [6] Rummich E., Nichtkonventionelle Energieumwandlung, TU Wien
- [7] Seme S., Štumberger G., Voršič J., The optimal tracking strategies for two-axis PV system. *Prz. Elektrotech.*, 87 (2011), Iss. 3, 170-174
- [8] Huld T., Šuri M., Dunlop E.D., Geographical Variation of the Conversion Efficiency of Crystalline Silicon Photovoltaic Modules in Europe, *Prog. Photovolt: Res. Appl.*, 16 (2008), 595-607
- [9] PVsyst V5.1 – Study of Photovoltaic system, *User's manual*, 2011

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