Annual Energy Harvest of LACARP Photovoltaic System

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Abstract— **Around the whole world, electric energy from photovoltaic systems is considered as an important generation alternative in the electric power system. A measure of the photovoltaic system's performance is given by the energy production as well as the system efficiencies, evaluated for different reference periods. In this paper, the photovoltaic system of LACARP Laboratory, Iasi, Romania has been presented and its performance indices have been evaluated. In this order, the performance of the grid connected photovoltaic system has been analyzed on annual, monthly and daily reference periods.**

Keywords-photovoltaic system; performance indices; yield.

I. INTRODUCTION

Accurate knowledge of the amount of energy production has fundamental importance for planning, designing and operating of the solar energy systems. The solar energy system includes that technology which converts the solar energy in a useful form of energy, the photovoltaic (PV) systems registering the highest growth among other sources.

The performance of PV system is evaluated comparing the amount of energy output from the entire PV system with the input irradiation on PV array, in order to evaluate the performance indices of the PV system. The performance of the PV systems depends on several parameters including the site location, the climate and eventually shadows. The shadow on PV system has a much greater effect on the solar yield than other kinds of losses.

The valuable information concerning the performance of the installation placement and PV system operation can be obtained from normalized values of energy yields and losses during different reference periods.

Actually, the estimation of these indices requires the energy data measurements. The measurement database behind of this study has been recorded using the LACARP photovoltaic system located on the Faculty of Electrical Engineering, Technical University of Iasi, Romania. The photovoltaic system has an installed capacity of 3 kW_p and is in operation since December 2013. The PV system has been continuously monitored during one year and the performance indices have been calculated. The PV system supplied 3012.34 kWh to the grid during 2014, ranging from 24 kWh in December 2014 to 480.46 kWh in July 2014.

The study conducted in this paper is presented according to the following sections. Section II presents a brief review of photovoltaic systems performance indices in accordance with European Standards. In section III, the photovoltaic system of LACARP Laboratory is described. Section IV focused on main PV performance indices in accordance with the energy output measurement database of photovoltaic system, which are analyzed considering different reference periods. Finally, the main conclusions of this paper are given in section V.

II. PHOTOVOLTAIC SYSTEM PERFORMANCE INDICES

In order to compare energy production and performance of different PV systems with different size and different locations, the PV systems performances are evaluated using their normalized performance indices such yields, losses and efficiencies. The yields are defined as energy normalized to peak power of the PV array or to irradiance at standard test conditions (STC).

The energy that could be produced by a PV system depends on irradiation incident on the PV array, which is related by the latitude of the PV system placement, the reflection coefficient around of PV array, tilt and azimuth angles, eventual shading or soiling of PV array, ambient temperature, technical characteristics of PV array, inverter efficiency, losses in wires and transformers, and so on. Therefore, the energy that could be produced is evaluated in accordance with the following performance indices, defined in [1]:

- the reference yield (Y_R) index of solar radiation on the surface of the PV array, depending on the meteorological characteristics of the site;
- the array yield (Y_A) index of DC energy that can be generated by PV array, depending on site characteristics and the PV array features;
- the final yield (Y_F) index of AC energy that can be generated by PV system, depending on site characteristics and the PV system features.

For PV system performance assessment, the daily (D), monthly (M) or annual (A) reference periods could be used, therefore the normalized yields will be denoted with a large indices (D, M, A), according with their reference periods.

The reference yield is established as ratio between the total orthogonal irradiation (kWh/m^2) and the array reference irradiance, calculated in STC (G_{STC}=1 kW/m^2, AM 1.5 spectrum, cell temperature 25 °C), during different reference periods (day, month or year).

$$Y_R = \frac{H_{ortho}}{G_{STC}} \quad (1)$$

The reference yield is expressed in hours and represents an equivalent number of peak sun-hours per day.

The array yield is defined as the DC energy output of the PV array, during the reference period, divided by the peak power of the installed PV array (nominal PV array power output under STC).

$$Y_A = \frac{E_A}{P_{PV}} \quad (2)$$

This index is expressed in (kWh_{DC}/kW_p) and represents the number of hours per day for which the array, operating at its rated output power, would have produced the same amount of energy.

The final yield is defined as the net AC energy of the entire PV system, during the reference period, divided by the peak power of the installed PV array.

$$Y_F = \frac{E_F}{P_{PV}} \quad (3)$$

This index is expressed in (kWh_{AC}/kW_{DC}) and represents the number of hours per day for which the PV system, operating at its rated output power, would have produced the same amount of net energy.

Losses are the differences between yields. The difference between reference yield Y_R and array yield Y_A is referred to as capture losses, L_C, which comprise thermal and miscellaneous capture losses. Thermal capture losses are attributable to the fact that maximum solar generator power output is usually lower than peak power because solar generator temperature generally exceeds temperatures at STC power output. Miscellaneous capture losses depends on different factors, such as the wiring, resistances and string diodes losses, maximum power tracking malfunctions, reduction of array power caused by inverter failures, modules' efficiency loss under low insolation conditions, permanently and temporary shadowing, dirt or dust accumulation or snow covering, etc.

The difference between array yield Y_A and final yield Y_F is referred to as balance of system BOS losses, $L_{BOS}=Y_A-Y_F$, which comprise all losses except for the previously mentioned capture losses. These include the losses in DC-AC inverter for systems that contain one or more inverters, and battery storage losses, for stand-alone installations.

The system efficiencies are defined as the yields normalized to array area, whereas the performance system (performance ratio) is defined as ratio between the final yield and the reference yield during the same reference period.

$$PR = \frac{Y_F}{Y_R} \quad (4)$$

A literature survey indicates that the annual PR differed significantly from a PV system to another, ranging between 0.25 and 0.9 with an average value of 0.66 [2-4]. It was found that well-maintained PV systems show an annual average value of PR around to 0.72.

III. LACARP Photovoltaic System Description

The photovoltaic system under analysis is located in Iasi, Romania, belonging of Faculty of Electrical Engineering, Technical University of Iasi, as part of LACARP Laboratory, a modern research laboratory developed as result of a research project of Power Engineering Department.

Fig. 1. View of LACARP PV system placement

The PV system has an installed capacity of 3 kW$_p$, the PV system being developed in order to operate as a grid connected or as a stand-alone PV system, depending on research objectives. In this paper are evaluated the performance indices of PV system as a grid-connected system.

The system consists of 12 polycrystalline silicon modules, SM-250PC8 manufactured by S-Energy, the main technical data are reported in Table I, in accordance with datasheet [5].

TABLE I. Technical Data of the SM-250PC8 Module at STC

SM-250PC8 - Polycrystalline silicon	
P_{max}	250 W
I_{sc}	8.67 A
V_{oc}	37.5 V
V_{mp}	30.8 V
I_{mp}	8.14 A
Coefficient of current K_{Isc}	0.052 % /°C
Coefficient of voltage K_{Voc}	- 0.312 % /°C
Coefficient of power K_{Pmax}	- 0.429 % /°C
Temperature of Operation	- 40 ÷ +85 °C
Nominal operating cell temperature	45±3 °C
No. of cells	6×10 matrix cells (156 × 156 mm^2)
Dimensions	1665 mm × 999 mm × 50 mm

The PV modules are interconnected in series and mounted on a dual-axis active tracking system. The double axis tracking system (DEGERtraker 3000NT/HD/CT) is managed by a Maximum Light Detection (MLD) control system, which ensures the optimal orientation of PV plane in order to maximize the amount of incident solar radiation for different levels of cloudiness.

The technical data of tracking system indicate a module surface area around to 25 m^2, having a weight of 600 kg, a 2.5m mast length and allows an azimuth angle range of 300° and an elevation angle range between 20 and 90°.

The PV modules are arranged in one string being connected to a Sunny Boy 3000 TL inverter, the inverter being tied by national grid to 0.4 kV. The inverter is equipped with an OptiTrack Global Peak management system with allows to find and use the optimal operating point of partially shaded PV modules.

Fig. 2. LACARP PV system

The solar measurement database behind of this study has been recorded using a Sunny WebBox module, which provide an interface between PV system and operator, as an interactive database that provide information about the hourly, daily, monthly and annual energy production.

The PV system has been continuously monitored to assess the performance of the system with the local power grid. Complete operation data for the year 2014 have been averaged for every 15 min during each month. Table II shows the monthly averaged total energy injected in the grid. The highest value of energy was in July with 480.46 kW and the lowest in December with 24 kWh. The 2014 annual energy production was 3012.34 kWh/year.

TABLE II. MONTHLY ENERGY PRODUCTION OF LACARP PV SYSTEM

Month	kWh/day	kWh/month	kWh/year
Jan	0.797	24.72	3012.34
Feb	2.26	63.54	
Mar	5.8	179.85	
Apr	10.67	302.19	
May	14.69	455.67	
Jun	15.81	474.34	
Jul	15.49	480.46	
Aug	13.89	430.6	
Sep	11.86	355.9	
Oct	5.4	167.66	
Nov	1.71	51.55	
Dec	0.77	24	

The solar measurement database used for analysis has been recorded using a Vantage Pro2™ wireless weather station. The weather station consists of two modules: the first one is the Integrated Sensor Suite which houses and manages the external sensor array, and the second one is the Console which provides the user interface, data display and calculations. The Integrated Sensor Suite is equipped with sensors for wind speed and wind direction (an anemometer with wind cup), a pyranometer with photodiode for UV and global irradiation, a barometer, a rain collector as well as the temperature and relative humidity sensors. All sensors are installed on a mast, in a position relatively free from any external obstruction and accessible for inspection and maintenance.

Fig. 3. The Integrated Sensor Suite and the Console modules of the Vantage Pro2™ weather station

In this study, the solar radiation database covers the year 2014. The measurements available in the database are characterized by one minute acquisition intervals, the hourly, daily and monthly average values being calculated after that some quality control tests were performed in order to identify the missing data and data that clearly violates the admissible limits. The solar radiation database is commonly available in two forms. The first form is the average values of global irradiation on a horizontal surface, whereas the second one is the average value of global irradiance on same surface.

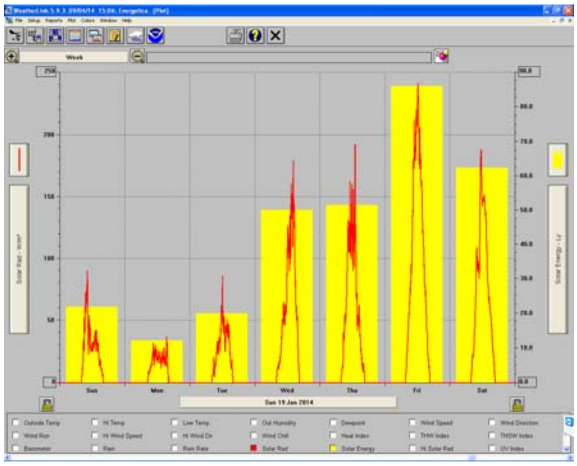

Fig. 4. Global irradiation measurements between 19th and 25th January 2014

Figure 5 shows instantaneous measurements of global irradiation for seven consecutive days from January 2014, whereas the numerical values of monthly global irradiation on horizontal plane are shown in Table III.

TABLE III. HORIZON HEIGHT ANGLES

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
G_h (kWh/m^2 /month)	24.69	38.99	84.50	96.98	150.51	135.31	149.61	152.42	125.86	67.33	27.61	21.74

IV. NORMALIZED ENERGY YIELDS ANALYZES

The geographical coordinates of placement of photovoltaic system are 47°9'11" (47.153) North, 27°35'34" (27.593) East and 39 m above the sea level [6], whereas the legal time is UTC+2. Solar energy potential for placement under analysis has been performed using the irradiation database and existing studies from sites recognized and recommended by the European Commission as well as the professional software in evaluating the potential of solar energy.

TABLE IV. DAILY VALUES OF SOLAR ENERGY POTENTIAL [4]

Month	G_h (Wh/m²/day)	β_{opt} (deg)	G_{opt} (Wh/m²/day)	D/B (-)	D_h (Wh/m²/day)	T_D (°C)
Jan	1100	65	1890	0.62	682	-1.1
Feb	1920	59	2990	0.52	998	0.2
Mar	3180	47	4160	0.49	1558	5.9
Apr	4270	31	4730	0.49	2092	12.7
May	5800	19	5810	0.43	2494	18.5
Jun	6130	13	5830	0.44	2697	21.5
Jul	6100	17	5960	0.42	2562	23.9
Aug	5550	28	6000	0.39	2165	23.2
Sep	4020	43	5100	0.4	1608	18.1
Oct	2560	58	3850	0.46	1178	12.2
Nov	1300	63	2140	0.6	780	7.1
Dec	901	67	1570	0.65	586	0.6

Solar potential on placement under interest expressed on daily reference period is:

- G_h: irradiation on horizontal plane: 3.58 kWh/m²/day;
- β_{opt}: optimal tilted angle: 37 deg.;
- G_{opt}: irradiation on optimal tilted plane: 4.18 kWh/m²/day;
- D/B: ratio of diffuse to global irradiation: 0.45;
- D: diffuse irradiation: 1.611 kWh/m²/day;
- TD: average of diurnal temperature: 11.9 °C.

Based on the average daily values of global and diffuse irradiation, monthly and annual values of solar energy potential have been calculated:

TABLE V. MONTHLY VALUES OF IRRADIATION

Month	Gh (kWh/m²/month)	Dh (kWh/m²/month)	Bh (kWh/m²/month)	Bort (kWh/m²/month)	Dort (kWh/m²/month)	Gort (kWh/m²/month	Kt
Jan	34.1	21.09	13.0	45.3	21.41	67.9	0.353
Feb	53.7	27.84	25.8	69.2	29.20	103.9	0.413
Mar	98.6	48.36	50.2	107.2	51.04	161.0	0.466
Apr	128.1	62.70	65.4	114.6	63.14	180.9	0.468
May	179.8	77.20	102.6	162.3	80.38	246.1	0.534
Jun	183.9	81.00	102.9	156.5	82.87	242.6	0.528
Jul	189.1	78.44	110.7	174.9	83.07	260.0	0.543
Aug	172.0	67.28	104.8	175.3	74.98	256.9	0.567
Sep	120.6	48.30	72.3	141.1	53.83	202.1	0.525
Oct	79.4	36.58	42.8	103.5	40.95	153.4	0.479
Nov	39.0	23.41	15.6	51.2	24.67	76.1	0.372
Dec	27.9	18.29	9.6	38.0	19.95	62.2	0.341

Solar potential expressed on annual reference period is:

- G_h: global irradiation on horizontal plane: 1306.1 kWh/m²/yr;
- D_h: diffuse radiation on horizontal plane: 590.48 kWh/m²/yr;
- B_h: beam radiation on horizontal plane: 715.7 kWh/m²/yr;
- B_{orth}: beam irradiation on orthogonal plane: 1339 kWh/m²/yr;
- D_{orth}: diffuse irradiation on orthog. plane: 625.5 kWh/m²/yr;
- G_{orth}: global irradiation on orthog. plane: 2013.1 kWh/m²/yr;
- K_T: clearness index: 0.497.

The shadow on PV system has an important effect on the system yield, especially the permanently shading resulting from the building's surroundings and also the temporary shading caused by the snow in winter season. Shading resulting from the building involves permanent shadows, which could be taken into account in the sun path. In this order, the horizon height angles of the surrounding buildings have been measured and tabulated in Table V.

TABLE VI. HORIZON HEIGHT ANGLES

Azimuth (°)	-90	-75	-60	-45	-30	-15	0	15	30	45	60	75	90
Height (°)	36	42	43	39	33	43	32	28	26	20	21	23	22

Concerning the irradiation taking into account the shading effect, the monthly values of irradiation are tabulated in Table VI, the global irradiation on orthogonal plane being 1293.90 kWh/m²/year.

TABLE VII. MONTHLY VALUES OF IRRADIATION WITH SHADOW EFFECT

Month	Gh (kWh/m²/month)	Dh (kWh/m²/month)	Bh (kWh/m²/month)	Gort (kWh/m²/month
Jan	34.1	21.09	13.0	10.4
Feb	53.7	27.84	25.8	24.7
Mar	98.6	48.36	50.2	90.0
Apr	128.1	62.70	65.4	131.4
May	179.8	77.20	102.6	206.3
Jun	183.9	81.00	102.9	215.8
Jul	189.1	78.44	110.7	225.2
Aug	172.0	67.28	104.8	198.8
Sep	120.6	48.30	72.3	118.3
Oct	79.4	36.58	42.8	51.8
Nov	39.0	23.41	15.6	12.5
Dec	27.9	18.29	9.6	8.7

To evaluate the PV system performance, the final yield, the reference yield and the performance ratio have been calculated. The effect of local and temporal irradiation differences is taken into account by the reference yield, which is obtained by dividing global irradiation on orthogonal plane to the irradiance under standard test conditions, for the reference period. A daily (D) reference period has been considered in the following analyzes. In order to disregard the size of PV system, all yields and losses values have been converted to normalized average daily yields and losses. Table VII shows the normalized monthly average of daily values of reference yield ${}^{D}Y_F$, array and system losses ${}^{D}L$, and final yield ${}^{D}Y_F$ in h/day for each month of 2014, as well as the monthly average of daily performance ratios of the LACARP grid-connected PV system, with and without shading effect.

TABLE VIII. REFERENCE YIELDS WITH (^{D}Y) AND WITHOUT ($^{D}Y^{0}$) SHADING EFFECT

Month	$^{D}Y_R$ (h/day)	^{D}L (h/day)	$^{D}L^{0}$ (h/day)	$^{D}Y_F$ (h/day)	$^{D}Y^{0}_F$ (h/day)	PR	PR^{0}
Jan	2.19	1.98	0.33	0.21	1.86	0.098	0.849
Feb	3.71	3.03	0.57	0.68	3.14	0.184	0.846
Mar	5.19	2.80	0.89	2.39	4.30	0.46	0.819
Apr	6.03	2.51	1.23	3.52	4.80	0.584	0.797
May	7.94	2.69	1.76	5.25	6.18	0.662	0.778
Jun	8.09	2.49	1.91	5.60	6.18	0.692	0.764
Jul	8.39	2.87	2.12	5.52	6.27	0.658	0.747
Aug	8.29	3.40	2.06	4.89	6.23	0.590	0.752
Sep	6.74	3.68	1.51	3.06	5.23	0.455	0.777
Oct	4.95	3.65	0.99	1.30	3.96	0.263	0.801
Nov	2.54	2.27	0.47	0.27	2.07	0.107	0.815
Dec	2.01	1.84	0.32	0.17	1.69	0.085	0.842
Year	5.52	2.77	1.19	2.75	4.33	0.499	0.786

Figure 5 shows the monthly average of daily final yield and total system losses. This type of chart is known as a normalized annual statistics chart. The monthly average of daily reference yield ranged from 2.01 in December to 8.39 h/day in July, whereas the final yield ranged from 0.17 in December to 5.6 h/day in July. The annual final yield of 2.75 kWh/kW_p/day.

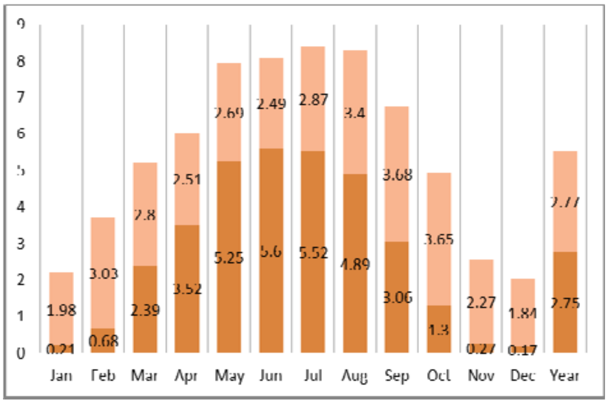

Fig. 5. Normalized annual energy yield statistics for the LACARP grid-connected PV system, P = 3 kW_p

The performance ratio is distributed within the range of 8.5–69.2%, whereas the annual value of performance ratio have been found 0.499, value that is in concordance with those found in literature, but that indicate a malfunction of the PV system.

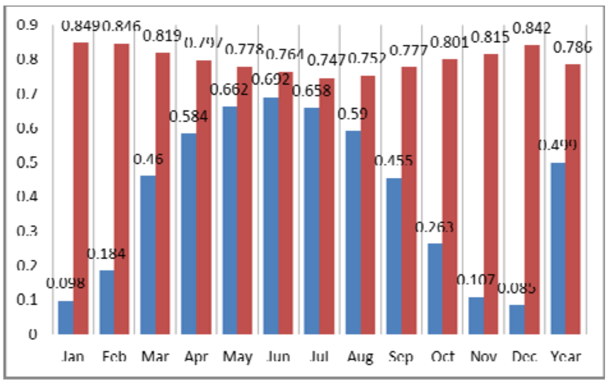

Fig. 6. Monthly performance ratio of LACARP grid-connected PV system with (blue) and without (red) shading effect

As can be seen in Fig. 6, the performance ratio values with shading effect are considerably lower from November to February than during the rest of the year. The system showed performance ratio as low as 0.5 due to the system shading. The most important causes for reduced performance ratio values are the permanently shading of surrounding buildings and the temporary shading of the snow. The PV panels under continuous operation eventually become covered with snow, decreasing the amount of light reaching by the panels, how happened between 25th January to 7th February 2014, and 29th December 2014 to 2th January 2015, respectively.

Table VII and Fig.6 shows also the normalized performance indices for each month of 2014, neglecting the shading effect and evaluating the amount of energy that is lost due to permanently shadowing. As can be seen from Fig.6, the performance ratios without shading effect are higher than values with shading effect, especially in winter season when the sun path has lower heights, the beam irradiation being obstruction by the surrounding buildings. Total losses of performance ratio as well as of amount of energy production are around 57% from actual production, equivalent with around 1717 kwh/year.

V. CONCLUSIONS

LACARP photovoltaic system generated above 3 MWh in 2014, ranging from 24 kWh in December to 480 kWh in July.

The effect of an installation's size can be analyzed using the normalized energy yield as well as the performance ratios during different reference periods. The permanent shadow is the most significant parameter that affects the PV system performance. For LACARP PV-system, the permanent shadow lead to a total loss in amount of energy around 57%.

The results of this study can help PV system owners to select the most economical solution for placement of PV systems in order to maximize the annual energy production. The installation of real-time monitoring system for PV systems allows improving the system performance ratio.

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