Proceedings of the 13th European Photovoltaic Solar Energy Conference & Exhibition, Nice, France, 23rd-27th, October 1995, pp. 1019-1022.

PERFORMANCE OF A 1.2 kWp STAND-ALONE PHOTOVOLTAIC SYSTEM IN MALTA

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ABSTRACT: The paper presents the results of the performance of a 1.2 kWp stand-alone photovoltaic (PV) system under local conditions, during two years of operation. The sizing and construction of the system were described elsewhere [1].

This is the first PV system to be tested locally. Monitoring and analysis of data as well as presentation of results were performed in accordance with the guidelines set by the Joint Research Centre - Ispra Establishment [2, 3]. The mean daily PV energy production was 3.034 kWh/kWp/day and the mean final yield was 1.89 kWh/kWp/day, with a performance ratio of 0.37.

Empirical equations relating the power produced to solar radiation are presented for future use. The accumulation of dust on the PV modules during summer did not contribute to more than 2% drop in power production while wind speeds higher than 2 m/s had a cooling effect on the PV modules. The major causes for drop in efficiency were shading and the deviation of the performance from the maximum power curve, caused by the accumulation of electric charge in the storage batteries [4].

1. INTRODUCTION

A 1.2 kWp stand-alone photovoltaic (PV) system with battery storage, had been set-up in Malta (latitude 35° 50′ N, longitude 14° 26′ E), with the aim of evaluating the potential of using PV systems for power production under local weather conditions [1].

Analytical monitoring was carried out for two years, as described in the guidelines set by the Joint Research Centre - Ispra Establishment [2]

This paper is divided into three sections:

1. Presentation of the results in accordance with the guidelines set by the Joint Research Centre - Ispra Establishment [3].
2. Presentation of more detailed information such as the effect of wind and dust accumulation on the performance of the system and the empirical equations arrived at, that correlate the power produced to the incident solar radiation.
3. Operational experience.

2. THE SOLAR POTENTIAL IN MALTA

During the operation of the system, data on solar global horizontal and inclined (36° to horizontal) radiation was collected, using silicon-based pyranometers. The mean global irradiation was found to be 4.705 kWh/m²/day and 5.302 kWh/m²/day, on the horizontal and inclined planes respectively.

Figure 1, shows a bar chart of the average monthly global horizontal *(IG)* and inclined solar irradiation *(IA)*, in kWh/m²/day and a curve joining the tilt factors for each month. The tilt factor is defined as the ratio of global radiation incident on an inclined surface to the global horizontal radiation measured at the same place. In this case the PV array plane was inclined at an angle of 36° to the horizontal, which is approximately equal to the latitude of Malta.

FIGURE 1: Bar charts of mean monthly global horizontal (white) and inclined (36° to horiz., black) solar radiation and a curve of the monthly tilt factors.

Figure 2 shows the frequency distribution of the mean daily in-plane irradiation at intervals of 1 kWh/m²/day, except for the first interval which is between 0 and 1.5 kWh/m²/day.

It can be deduced that only 3.83 % of the days have solar radiation lower than 1.5 kWh/m²/day and this corresponds to about two weeks per annum. Moreover, it was noted that the maximum number of consecutive days that received less than 1.5 kWh/m²/day on the PV array plane was three days occurring once in January 1995.

Figure 2: Frequency distribution of mean daily in-plane solar irradiation.

3. RESULTS OF THE PV SYSTEM PERFORMANCE

The most important indicator of the PV system is the performance ratio *(PR)*. The *PR* is defined as the ratio of the useful output energy to the total solar energy incident on the PV array. It is independent of the size of the PV system or the available solar radiation and this enables a comparison between the yield of different systems around the world.

Here, the mean *PR* over two years was found to be 0.37. This value exceeds the average *PR* of 0.34 of the professional PV stand-alone systems that were tested in the Thermie Programme [5].

Table 1, shows the mean monthly results that describe the performance of the system. All calculations were based on the total area of the PV array of 11.117 m².

The drop in the *PR* during the last few months is caused by the deterioration in the battery performance.

The mean daily array yield was plotted against the inclined solar irradiation as shown in figure 3.

Two line fits are presented for the 730 data points. The first is a linear fit passing through the origin, while the second is a second degree polynomial, as shown below:

TABLE 1: Mean monthly performance results of the PV system.

	Y_r	Y_a	Y_f	L_c	L_s	*PR*
Jl-93	6.64	2.73	1.85	3.91	0.87	0.28
Au-93	6.6	3.13	2.05	3.47	1.08	0.31
Se-93	5.92	3.14	2.25	2.78	0.89	0.38
Oc-93	4.59	2.87	2.13	1.72	0.74	0.46
No-93	3.77	2.18	1.51	1.59	0.67	0.40
De-93	3.37	2.32	1.69	1.05	0.63	0.50
Ja-94	3.52	2.34	1.65	1.18	0.69	0.47
Fe-94	4.52	2.41	1.64	2.11	0.76	0.36
Mr-94	5.83	3.62	2.43	2.21	1.19	0.42
Ap-94	5.37	3.36	2.30	2.01	1.06	0.43
My-94	6.52	3.93	2.50	2.59	1.43	0.38
Jn-94	6.52	3.73	2.71	2.79	1.02	0.42
Jl-94	6.62	3.61	2.46	3.01	1.15	0.37
Au-94	6.54	3.61	2.14	2.93	1.46	0.33
Se-94	5.77	3.30	1.66	2.47	1.63	0.29
Oc-94	4.46	2.83	1.82	1.64	1.01	0.41
No-94	4.08	2.58	1.58	1.50	1.01	0.39
De-94	3.72	2.48	1.63	1.24	0.84	0.44
Ja-95	3.48	2.39	1.37	1.09	1.03	0.39
Fe-95	5.14	2.85	1.36	2.29	1.49	0.26
Mr-95	5.57	3.12	1.45	2.45	1.67	0.26
Ap-95	5.75	3.17	1.51	2.58	1.67	0.26
My-95	6.60	3.76	1.76	2.84	2.00	0.27
Jn-95	6.43	3.51	1.96	2.92	1.55	0.30

where, Y_r = reference yield, defined as the ideal yield of the PV array at 100% efficiency, and is equal to IA/HA_{ref}, where HA_{ref} is the reference in-plane irradiation taken as 1 kW/m².

Y_a = array yield = EA/P_{nom} x n, where EA is the array output energy in kWh, P_{nom} is the nominal power of the PV array given as 1.2 kWp and n is the number of days;

Y_f = final system yield = EB^-/P_{nom} x n, where EB^- is the output energy from the batteries;

L_c = capture losses = Y_r -Y_a and;

L_s = the system losses = Y_a -Y_f.;

PR = performance ratio = $Y_f/(Y_r$ x total array area).

FIGURE 3: Daily Array Yield (kWh/kWp) vs. In-plane Irradiation (kWh/m²/day).

1. Straight line equation passing through the origin:

EA/P_{nom} = 0.675 x IA, having a coefficient of determination, $R^2 = 0.98$.

2. Second degree polynomial:

$EA/P_{nom} = - 0.050 \times IA^2 + 1.011 \times IA - 0.175$, with $R^2 = 0.82$.

The linear fit has a higher R^2 value but it gives a lower estimate of the array output for solar radiation less than 4 kWh/m²/day. The percentage of solar radiation values that are less or equal to 4 kWh/m²/day is 35%, as seen from figure 2.

On the other hand, the polynomial curve has a lower R^2 value but it is offset from the origin and this physically represents the internal consumption of the battery control unit. Also, the curve bends down at higher radiation values, which represents the diversion of the PV array output from its ideal linear relationship with solar radiation, due to its elevated operating temperature. Higher degree polynomials did not improve on the statistical correlation for this system.

It is worth mentioning that the linear relationship fitted best for hourly data plots of EA/P_{nom} vs. IA for each month.

The results obtained from monitoring the batteries showed that the batteries have weakened by time, even though proper maintenance and occasional charge boosting was ensured.

Figure 4 shows the mean specific gravity plotted against time for consecutive charge-discharge days. Readings were taken once a month in the evening of a bright day and the dawn of the next day.

The batteries used were heavy duty lead-acid traction batteries. Though this type is not ideal for PV systems, it was the only option at the time.

The battery bank and the battery control unit were considered together. The results showed an average amp-hour (Ah) charge efficiency of 72.2% and a Watt-hour (Wh) energy efficiency of 62.6%. The Wh efficiency is equal to the Ah efficiency multiplied by the ratio of the discharging voltage to the charging voltage of the batteries.

FIGURE 4: A topographical view of the mean specific gravity of the batteries for different consecutive charge/discharge days of different months, normalised to 25 °C.

4. PERFORMANCE OF THE PV ARRAY

Besides temperature rise of the PV cells, there is another factor which negatively affected the array efficiency. During most of consecutive sunny days, the batteries reached a high state of charge in the afternoon. As a result the voltage of the battery bank increased and forced the array to operate further away from the maximum power point which is situated at the knee of the I-V characteristic curve of PV cells [4].

Figure 5 clearly explains this behaviour during July 1994. The drop in efficiency between 11 a.m. and 2 p.m. is caused by the temperature rise of the cells. In the afternoon, though the cells cooled down to a temperature that was less than the corresponding hour in the morning - taking noon to be the mid-point - and the solar radiation was higher than the corresponding hour, the output of the PV cells decreased all the same, because of the above mentioned reason.

The efficiency drop after 4 p.m. was due to partial shading caused by a tree.

The ability of wind to cool the PV modules became effective for wind speeds higher than 2 m/s. For example, from the 15-minute data of sunny days in July 1994, it was clear that there is a steady drop in the temperature difference between the modules and the ambient, reaching a maximum of about 6 °C, at a wind speed of 3 m/s.

FIGURE 5: Graphs of the PV array efficiency vs. time for days with bright sunshine conditions in July 1994.

As for dust accumulation, its maximum effect appears just before the first rain. Using the data collected in August 1994, two days were chosen, one before and one after the rain. Both days had an almost identical distribution of array temperatures and solar radiation, as well as a constant delivery of power from the batteries to the load throughout the previous nights. From the data it could be concluded that the gain in the array efficiency after the rain was 2%.

5. OPERATIONAL EXPERIENCE

The main operational experiences are:
1. Protection of outdoor electronic equipment from humidity, is essential for their proper operation.
2. Routine check-up of the batteries and the battery control unit are required to avoid breakdowns.
3. For Malta, it is not so important to wash the PV modules in summer.
4. Considering the seasonal availability of solar radiation, a close follow-up and management of the electric load is a key factor towards the optimisation of the output of a stand-alone PV system.

6. CONCLUSIONS

During the two-years of monitoring, the 1.2 kWp PV array produced 2.658 MWh, which corresponds to an average of 3.034 kWh/kWp/day. The useful output energy from the batteries amounted to 1.655 MWh, or in other words, an average daily energy delivery of 2.268 kWh/day.

Table 2 shows a summary of the results obtained during monitoring. These values represent the means over the period of testing.

TABLE 2: Mean performance values over two years.

Reference yield *(Y_r)*, kWh/kWp/day	5.302
Array Yield *(Y_a)*, kWh/kWp/day	3.04
Final Yield *(Y_f)*, kWh/kWp/day	1.892
Array Efficiency	6.28 %
System Efficiency	3.94 %
Combined Battery and Battery Control Unit Ampere-hour Charge Efficiency	72.2%
Combined Battery and Battery Control Unit Watt-hour Energy Efficiency	62.6%
Performance Ratio	37%

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