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INCREASING PV MODULE OUTPUT WITH FLAT REFLECTORS – A SCENARIO IN MALTA

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ABSTRACT: The output of photovoltaic (PV) modules is related to the solar radiation incident on their surface. The immediate surroundings of the modules may reflect a considerable amount of radiation on to them, thus affecting their performance and output. This paper explores ways of improving the output of PV modules installed in Malta, with the aid of flat plate reflectors installed in front of the modules. This study focused on the effect that different types of reflective materials have on the PV modules' output. Two sets of reflectors were studied. The first set consisted of reflectors that can be set at an angle to the horizontal, while the second set emulates different flat roof surfaces. The output of PV modules was measured and compared for each case. Measurements started in October 2012 and are still ongoing. The aim is to study the effect of reflecting surfaces and the PV modules output, and to determine the effect of the inclination of reflector. Results have so far shown that a potential increase of up to 15% maybe achieved by aluminium reflectors during the winter seasons.

Keywords: Flat reflectors, reflected radiation, PV module output.

1 INTRODUCTION

1.1 Theoretical background

The solar radiation on a plane is composed of beam radiation (B) and diffuse radiation (D). It can be expressed by:

$$G_{total} = B + D$$

The diffuse component is further divided into atmospheric diffuse radiation (D_a) caused by airborne particles, clouds and the air mass itself, as well as ground diffuse radiation (D_g), which is mainly reflected from surfaces, trees and the ground itself. The amount of radiation reflected off a surface depends on the surface's albedo ρ. Thus radiation reflected off the ground D_g can be expressed as $\rho_{ground}(B+D_a)$ [1]. Thus, if the PV modules are installed on ground surface or facing objects having a high albedo value, the amount of diffuse reflection from the ground can be substantially increased.

1.2 Review of previous studies

The use of reflectors to increase the energy yield of solar thermal collectors and PV modules has been studied by a number of authors.

Hiroshi Tanaka calculated the optimum angle of inclination of the solar collector as well as the inclination of reflector for a location with latitude of 30ºN [2]. Ljiljana Kostic et al carried out also experimental work to determine the optimum angle of reflectors (below and above) of thermal collector mounted at 45º to the horizontal and latitude of 43.3º N. [3]. Another study suggested that for solar systems that are installed in rows on a horizontal surface, the space between the rows may be covered by a reflector from the top of the front panel to the lowest point of the panel behind [4]. The distribution of irradiance on PV modules is more critical than on thermal collectors, due to the fact that they are normally connected in series. Furthermore, crystalline PV cells are more sensitive than thin film cells to non-uniform solar distribution.

On the other hand, temperature rise due to high irradiance may become a limiting factor for additional power production, since PV module efficiency drops with increased temperature [5]. Thus, stationary specular reflectors are not suitable for PV systems, as the variation of reflected solar radiation results in a non-uniform distribution of radiation on the panels [6]. Other studies considered fixed modules with tracking reflectors [7], the effect of ground reflectance on bi-facial PV modules [8], and choice of material for reflectors [9].

All studies reported an increase in the energy yield, both thermal and electrical. The gain increase varies according to application, setup, material used and site related factors.

1.3 Local scenario

In Malta (Lat 35.9°N, 14.4°E), most PV module installations are located on a flat horizontal roof or surface. Thus the possibility of radiation reflected from the ground on to the modules is unavoidable and the ground reflectance can be substantial. Further, if a reflector is placed in the space in front of the PV modules, the reflectance on them can be further increased. During the hot summer months, the effect of the reflectors may be limited due to rise in PV cell temperature [5].

This paper studies these two effects separately. One effect is that of the roof surface on the output of the modules, and the second one is to have reflectors of different materials placed in front of PV modules.

2 THE SETUP

2.1 Hardware setup

Two sets of four PV modules each were used in this study. The sets were mounted as follows, with the PV modules installed at an angle of 36 degrees to the horizontal and facing south:

Set 1: Roof reflectance.

The surface in front (to the south) of the PV modules was treated in such a way to simulate flat roof finishes commonly found in Malta – concrete, dark coloured waterproof membrane, light coloured roof paint. One surface was not treated, and was considered the benchmark against which the effects will be measured.

Set 2: Inclined reflectors.

Three inclined reflectors covered with aluminium foil, aluminium sheet and white paint were placed in front of the second set of PV modules. The angle of inclination of reflectors was varied at intervals of 0, 15, 20, 25 and 30 degrees to the horizontal, on different days. These reflectors were inclined towards the North.

It is expected that the reflectors will be more effective in winter, when the sun's elevaion is lower, and the reflected radiation onto modules by the reflectors is more significant. The sun's azimuth during hours of significance solar radiation varies between ±50°. The area of treated roof surface and reflectors measured 120cm by 120cm each, so the width of reflector is at least twice that of the PV modules. This size of reflector is sufficient and the radiation on the modules will be nearly uniform, even when the sun's azimuth is away from the geographical south.

2.2 PV modules setup

One set of PV modules had a peak power of 10 Watts, while the other was at 20 Wp. All PV modules had a voltage of 17.82 Volts at the maximum power point. The current at maximum power delivered by the modules were 0.57 A and 1.14 A, respectively. At such a low power output, it was not possible to find a micro-inverter or an MPPT tracking device to load the panels and operate them at their maximum power point. Also, an energy meter to measure the output of each module was not available.

A solution was devised whereby the electrical load connected to the panels was chosen to be a resistor that allows the panels operate very close to the voltage and current of their maximum power point. The modules will not be loaded at the optimum point at all times, and the energy produced will be less than the maximum available. However, as all modules are connected to the same load, the ratio of their outputs will be practically the same, even when connecting different loads. Thus, for the 20 Watts modules, a resistor of 15 Ω (17.82 Volts / 1.14 amps) was chosen, being the nearest standard value of resistance available. The wattage of resistor was 20 Watts, to absorb the PV module's power. Similarly a 10 Watt, 33 Ω resistor was connected to the 10 Watts modules.

Once this electronic setup was accomplished, the system was connected to a dedicated computer and monitored for the output voltage and current every minute from 8.00am till 4.00pm. The average power and hence the energy, was calculated for each minute of the recording interval.

Measurements had started in October 2012 and were taken every day till the end of February 2013. However, it is intended that readings will continue for a period of one year, to include greater seasonal variability in the study.

The 10 Watts modules were initially placed in front of the tilted reflectors, with the narrow side nearest to the ground. The 20 Watts modules were facing roof areas finished in different materials, with the longest side horizontal. Then, from 1 December 2012, the PV modules were swapped.

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2.3 Selection of materials

The choice of materials to be used as ground reflectors was governed by what is most frequently used as roof finishes by the local building industry. These are concrete/cement, dark waterproofing membrane and light colour waterproofing paint.

The choice of materials for the inclined reflectors was determined by their cost and availability. Materials that satisfy these criteria were aluminium foil, aluminium sheet and white oil-based paint. The aluminium foil is more reflective but less flat than the aluminium sheet.

The setups of both systems are shown in Figures 1 and 2.

Figure 1: PV modules in front of paint, cement and waterproofing membrane, covering horizontal flat roof. The fourth module is the reference.

Figure 2: PV modules in front of three inclined reflectors covered with aluminium foil, aluminium sheet and white painted board. The module of the right was the reference module.

2.4 Data logging

The voltages from the modules were connected to an analogue to digital converter PCI computer card, Avantech PCI 1713-U. The main characteristics of the A-D converter are shown in Table 1, below.

Table 1: Characteristics of the A-D converter.

Inputs	32 single ended, or 16 differential, or combination
Input range	0 ~10 V, 0 ~ 5 V, 0 ~ 2.5 V, 0 ~ 1.25 volts
Isolation protection	1000 V
Sampling rate	100 kHz
Input impedance	1 GΩ
Gain	1, 2, 4, 8
Accuracy	12 bit

The data was captured onto the hard disc for analyses. The A-D converter has an input range of only 10 volts, while the output of the PV modules was expected to be near 20 volts. So a simple voltage divider, consisting of two 10 kΩ resistors in series (giving a factor of 0.5), was used to bring the output of the PV panels just in the range of the analogue card. The PCI card input was connected to the mid-point of the resistors, while the PV modules connected at the top of resistors. The electrical load of these resistors is negligible, being only 0.02 Watts.

2.5 Correction factors

The modules, although similar in material and manufactured in the same batch, may have some mismatch in their outputs. Similarly, the electrical loads, the voltage dividers and the A-D convertor channels may introduce some measuring errors. To correct for these errors, each set of modules were exposed to the sun in an identical way for a number of days – all facing south and inclined at the same angle to the horizontal, and laying on a similar horizontal flat surface. The output of each PV module was measured as described above. From the sum of the energy outputs over several days, a factor for each module relative to the benchmark module was found. This factor was then used in the subsequent calculations during the evaluation of the reflecting surfaces.

This approach was possible because this study compared the relative outputs of different modules, and as such, the absolute values were not important.

3 RESULTS and DISCUSSION

3.1 Parameters

The effect of reflector and PV module combination depends on a number of factors, including the elevation of the sun, the angle of inclination of the modules to the horizontal and the angle between reflector and modules.

In this study, the PV modules were always fixed at 36 degrees to the horizontal, the treated roof surfaces always horizontal, while the inclination of the reflectors varied from 0 to 30 degrees to the horizontal and facing the North. The sun's elevation varies with the time of the day and day of the year. So the results were grouped and analysed on monthly intervals.

3.2 Roof reflectance

Readings of the roof surface reflectors started on 10 November 2012. For the following twenty days, the average output energy per minute was calculated and summed up. The relative outputs from the different surfaces are given in Table 2 below. The reference output is designated by 1 (100%).

The waterproofing paint gave a 9.0% increase in output, when compared to the benchmark roof surface. The gain from the cement surface was negligible while the membrane gave lower output than the reference roof.

After 3 December 2012, the 10-Watt and 20-Watt modules were interchanged. Thus, the 10 Wp modules were now facing the horizontal roof surface reflectors. During the period 3-12 December 2012, it was noted that the same roof surface as above had the best performance, but the percentage was only 3.6%. From 13 till 23 December, the performance of the painted surface was 2.18%, giving an aggregate of 2.8% for the month of December 2012.

Table 2: Relative PV output when facing different horizontal reflectors.

Roof	Paint	Cement	Membrane
1	1.090	1.016	0.987

During the month of January 2013, the best performance was achieved by the cement surface, at 6.5 %. For the month of February, the paint surface again had the highest output by 3.7%. The results are summarised in Table 3.

Table 3: Comparative outputs of PV modules facing different roof surfaces.

	Roof	Paint	Cement	Membrane
Nov 12	1	1.090	1.016	0.987
3-12 Dec 12	1	1.036	0.995	1.020
13-23 Dec 12	1	1.022	0.978	0.984
Jan 13	1	1.016	1.065	1.004
Feb 13	1	1.037	1.005	1.00
Overall *	1	1.049	1.017	0.997

**Overall performance was calculated by summing the energy outputs for the months November2012 – February 2013*

More studies may be required to fully explain the results obtained. However, one may point the following site observations:

a) The weather in November 2012 was milder than the following four months and the PV modules were oriented with their longer side nearer to the reflecting surface. This may have provided better capture of reflected radiation.
b) The rain and dew affect the reflectivity of the roofs' surfaces. This contributes to changes in the radiation reflected onto the modules, especially during the winter months, when the sun's elevation is lowest.
c) The drop in performance of the painted surface from 9% to 3.6% may be due to rapid change of fresh paint surface due to ageing, or due to change in PV module orientation. One has to monitor the long term performance of this surface for more reliable conclusions.

3.2 Reflectors performance

The performance of the reflectors in this study had two independent variables, namely the material composition and the angle of inclination. The angle of inclination was set at 0, 15, 20, 25 and 30 degrees all day on consecutive days. Thus within one week, one full day of measurements at each inclination was recorded. Each variable is considered separately as shown below.

3.2.1 Material of reflector

The output of the PV modules for each type of reflector, irrespective of its inclination, was added up for each recording period and tabulated in Table 4.

The overall result, calculated over the four-month period, suggests that the inclined reflectors are effective. The increase in output is substantial, an average of nearly 10%.

There were instances when the inclination of reflectors was 25 or 30 degrees, so that the reflectors themselves cast a shadow on the PV modules, both in front and to their side. This obviously lowers the energy output of the PV modules.

Table 4: Comparative outputs of PV modules facing reflectors of different materials.

	Roof	Foil	Aluminum	White
Nov 12	1	1.075	1.069	1.060
Dec 12	1	1.149	1.106	1.074
Jan 13	1	1.090	1.136	1.114
Feb 13	1	1.064	1.126	1.119
Overall*	1	1.089	1.110	1.094

**Overall performance was calculated by summing the energy outputs for all months*

3.2.2 Angle of inclination of reflector

The angle of inclination of the reflectors had five settings: 0, 15, 20, 25, and 30 degrees to the horizontal and facing North. The results are compared first month by month in Table 5 and then globally in Table 6.

Overall, it may be concluded that a reflector made of aluminium sheet inclined at 20° to the horizontal, in front of a PV module, will give the best overall result for the months November – February. The expected energy gain is 15.2%. Figure 3 below represents the data graphically.

Figure 4 represents the performance of the aluminium sheet reflector at each angle of inclination over the months November – February. It shows that an angles inclination of 15° and 20° to the horizontal gives a performance gain in excess of 10% for all the months. On the other hand, at 30°, the decrease in performance over the entire period is very evident, especially during months when reflector casts shadow on the PV module itself.

Table 5: Comparative outputs of PV modules facing reflectors that were inclined at different angles.

	Roof	Foil	Aluminum	White
		0°		
Nov 12	1	1.054	1.008	1.041
Dec 12	1	1.156	1.099	1.042
Jan 13	1	1.062	1.092	1.074
Feb 13	1	1.032	1.056	1.080
		15°		
Nov 12	1	1.096	1.116	1.074
Dec 12	1	1.179	1.155	1.097
Jan 13	1	1.139	1.196	1.160
Feb 13	1	1.071	1.138	1.111
		20°		
Nov 12	1	1.101	1.120	1.067
Dec 12	1	1.204	1.168	1.111
Jan 13	1	1.108	1.170	1.140
Feb 13	1	1.080	1.152	1.118
		25°		
Nov 12	1	1.077	1.065	1.084
Dec 12	1	1.128	1.078	1.086
Jan 13	1	1.068	1.111	1.123
Feb 13	1	1.070	1.145	1.143
		30°		
Nov 12	1	1.033	1.001	1.029
Dec 12	1	1.048	0.982	0.999
Jan 13	1	0.949	0.932	0.959
Feb 13	1	1.065	1.134	1.139

Table 6: Overall results of power output from PV modules facing reflectors that were inclined at different angles for the period November 2012 – February 2013.

	Roof	Foil	Aluminum	White
0	1	1.075	1.088	1.068
15	1	1.121	1.145	1.101
20	1	1.123	1.153	1.109
25	1	1.086	1.100	1.109
30	1	1.046	1.034	1.057

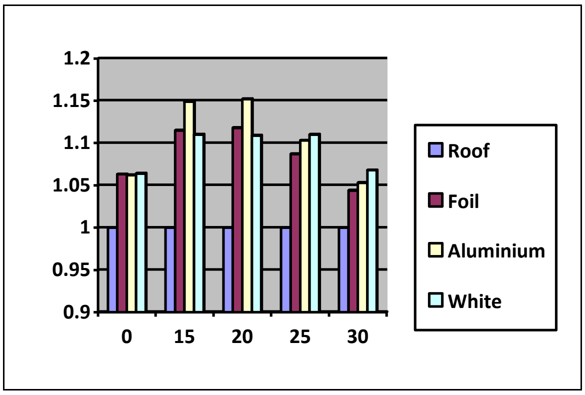

Figure 3: Overall output of PV panels facing inclined reflectors – from November 2012 till February 2013

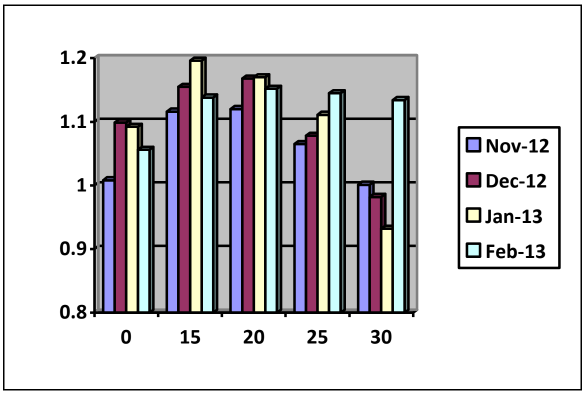

Figure 4: The normalized output of aluminium reflector for each angle of inclination, over the four months of testing.

3.2.3 Limitations

The duration of measurements is not representative of a whole year, and the gain of reflectors may change throughout the seasons.

The results in this study were measured during the autumn and winter seasons. Hence, on many days there were lots of cloud cover and precipitation. These will hinder the evaluation of the effectiveness of and the comparison between the reflectors.

When the inclination of reflectors in 25° or more, the reflectors may cause shading on the PV modules. This is more pronounced in December and January, when the maximum sun's elevation is about 33°. Further, when the sun is to the east of the PV modules, the first reflector may cast a shadow on the second module. Thus the first module will be less covered by shadow than the rest. This created imbalance in shading during the early hours, say up to 9.30am. The same is true when the sun is to the west of the panels. To compensate for this effect, one has to limit the measurements from 10.00am till 2.00pm during those months.

4 CONCLUSIONS

The results above indicated that the electrical energy generated by PV modules is increased by an average of 4.9% if they are installed on flat surface that is painted with a light colour. The cost of the paint to treat the surface is negligible, when compared to the cost of the PV system. So treating the roof surface with such paint is a cost effective way to increase the output of the PV system.

By using reflectors as above, the increase in output can be up to 15.2%, using aluminium sheet reflector at 20° to horizontal. Aluminium sheet is more expensive than paint or aluminium foil, but it is more durable and could still be cost effective. However, even white painted reflector gave an appreciable increase of 10.9%. This surface could be preferred over aluminium foil because it needs less maintenance.

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