FIRST-HAND EXPERIENCE OF SOLAR PHOTOVOLTAIC GRID-CONNECTION IN MALTA

Charles Iskander & Edward Scerri

Institute for Energy Technology, University of Malta
Triq il-Port Ruman, Marsaxlokk, ZTN 09, Malta
Phone: ++(356) 650675, Fax: ++(356) 650615, e-mail: iskander@global.net.mt

ABSTRACT: The paper presents the design, set-up and commissioning of the first grid-connected solar photovoltaic system in Malta. Some preliminary results are also included. The aim of this project was to study the state-of-affairs of such systems when they are interfaced with the local electricity grid. This would lead to a better understanding of such interfaces thus enabling the formulation of definite policies and guidelines in preparation for the wide-spread application of such systems in the near future.
Keywords: Grid-Connected - 1: Performance - 2: Sizing - 3

1. INTRODUCTION

Following the recommendations given in a previous publication [1] and based on the experience gained in operating stand-alone photovoltaic *(PV)* systems [2, 3, 4], a grid-connected *PV* system was designed and commissioned at the Institute for Energy Technology (latitude: 35.835° N, longitude: 14.543° E).

At the moment, the attention of the Institute is focused on the needs of the domestic rather than the commercial or industrial sectors. The reasons for this choice are fourfold. Firstly, the domestic sector in Malta consumes more than 30% of the total annual electricity sold by the National Electricity Utility, Enemalta [5]. Secondly, there is a continuous increase in the demand for electricity by this sector alone, of about 5% annually. Thirdly, the use of *PV* systems in dwellings could encourage energy conservation and efficient use of electricity. Fourthly, the availability of unutilised flat roofs in most residential buildings provides free space to place *PV* modules in Malta, where land is very limited and costly.

2. SIZING OF THE *PV* GRID-CONNECTED SYSTEM

This system is sized to cater for most of the electricity needs of a family of four in Malta, excluding water heating. It would be sensible that before installing such a system, the family would first consider buying a solar water heater for their dwelling: It is more efficient to heat water by direct absorption of solar energy. Sizing will be based on an average daily consumption of 7 kWh.

Assuming the mean performance ratio *(PR)* of a grid-connected system to be 0.75 and knowing that the mean daily solar radiation incident on the plane of the *PV* modules (36° to the horizontal) in Malta, is 5.302 kWh/m² [2], the nominal *PV* array power could be calculated from the equation [6]:

$$PR = Y_f / Y_r \qquad (1)$$

where, Y_f = final yield of the system (kWh/kWp);
= final output energy from inverter/ nominal *PV* array power;
= $7/P_{nom}$;
and Y_r = reference yield of the system [(kWh/m²)/(kW/m²)];
= inplane irradiation/reference inplane irradiance (1 kW/m²);
= 5.302/1

Hence, substituting in equation (1), P_{nom} was found to be 1.8 kWp.

Using this value in the PVFCHART software [8], yields a long-term mean energy output of 6.85 kWh/day, which is sufficiently close to the required energy of 7 kWh.

3. CHOICE OF *PV* MODULES AND BALANCE OF SYSTEM (BOS) COMPONENTS

Thirty, 60 Wp each, SOLAREX *PV* polycrystalline modules were arranged in five parallel strings. Each string had six modules connected in series.

The inverter chosen was a 1.8 kW, SMA PVWR 1800S, which could be operated in a single-phase system. It can also be placed in a three-phase system, by making minor adjustments. According to specifications, the inverter operates at high efficiencies at all loads and has the facility of data monitoring via a serial port.

A d.c. control box consisting of properly rated fuses, blocking diodes and over-voltage protection was also installed. Other BOS components such as cables, circuit breakers and supporting structure were purchased locally.

The modules were arranged in two arrays as shown in figure 1. The roof of the Institute could not take any extra load due to construction limitations, so that the beams had to rest on the edges of the roof.

The *PV* system was placed facing the geographic South and secured to the roof. Electric cables were passed from each of the five strings to the d.c. control box. A common output was then wired to the inverter. The input and output from the inverter were protected by separate 2-pole circuit breakers. Earthing of the whole system was carried out and tested.

Figure 1: Photograph of the *PV* system placed on the roof of the Institute for Energy Technology.

4. EVALUATION OF SHADOWING & WIND EFFECT

4.1 Shading Calculations:

Shading of the first array onto the second one was to be totally avoided on 21st December – the day with longest shadow – between 8:00 and 16:00 (G.M.T. + 1 hour). Solar radiation levels before and after these hours are relatively low during this month. This exercise would maximize the output of the system.

In order to arrive at the required distance between the two arrays, the solar elevation (ν) and the solar azimuth (ψ) for that day were calculated as 7.984° and -53.35°, respectively.

Each array consisted of two rows of modules, placed end to end and laid length-wise at an angle of 36°, to the horizontal, as shown in figure 1. The effective height between the top end of the *PV* modules of the first array and the lower end of those in the second array was 1300 mm. Hence, Length of shadow l, can be calculated as:

l = Height * cot ν;
= 1300 * cot 7.984 (at 8:00 a.m.)
= 9269 mm.

This shadow would be at an angle equal to the azimuth, ψ. Therefore, the distance d, between the two rows of modules should be:

d = 9269 * cos (-53.35)
= 5533 mm.

However, part of the shadow cast by the edge of the first array could lie beyond the opposite edge of the second array, depending on the length of the second array. A condition might arise where the required minimum distance between the two arrays could be less than 5533 mm. This had to be checked as follows:

Span of second array = 4600 mm.
Therefore, the space between the two arrays could be reduced to:
= 4600 * cot 53.35
= 3422 mm.

This would optimise the use of the roof area.

The same result is expected for the afternoon, since at 16:00, the azimuth would be numerically equal to that at 8:00. This is strictly true if both arrays are facing the true geographical South and there is no lateral displacement between them, as in this case.

4.2 Wind Force Assessment

Long-term statistical wind data for Malta, show that maximum wind gusts V_{ref}, registered at a height h_{ref}, of 10 m, are in the region of 30 m/s. This corresponds to a wind speed V_{req}, of about 20 m/s at a height h_{req}, of 3 metres, where the solar modules are situated. The equation that interpolate wind speeds at different heights is given by:

$$\frac{V_{ref}}{V_{req}} = \left(\frac{h_{ref}}{h_{req}}\right)^{\alpha} \quad ; \qquad (2)$$

where, α = roughness factor;
= 1 (for built-up areas).

The *PV* array could be approximated to a thin flat plate. Classical equations of lift force (L) and drag force (D) apply as follows [7]:

$L = 0.5 \rho v^2 A c_l$ (3)
where, ρ = density of air
= 1.225 kg/m^3, at standard conditions;
v = wind speed
= 20 m/s max. gust (long-term statistical results);
A = plate area (span x chord)
= 4.6 x 2.2 m;
c_l = 2π x sin α,
where α = incidence angle;

Hence, L = 9 kN

The system had to be secured to the roof since the lift is greater than the total weight of the system of 4 kN. Spacing of about 20 mm were allowed between the *PV* modules to reduce wind loading.

Similarly, the drag force, D can be found from the equation:

$D = 0.5 \rho v^2 A c_d$; (4)
where, c_d = drag coefficient, (for a flat plate, c_d varies with the span to chord ratio [7]).
= 1.165.
Hence, D = 2.8 kN.

This force should be balanced by the frictional force (F) between the array and the roof.

F = μR;
where, μ = coefficient of friction;
= 0.8;
and, R = weight of array;
= 4000 N;
Hence, F = 3.2 kN.

5. DATA COLLECTION

Data is being continuously collected using a 21X Campbell micro-logger together with the micro-processor of the inverter. The data being collected is 15-minute averages of 10-second instantaneous readings. To increase reliability of data collection, the 21X data-logger has been powered by an external battery, being charged by a dedicated solar module.

The following data is being gathered:

- Global solar radiation on the horizontal plane and on the plane of the array;
- Ambient temperature and relative humidity;
- Rainfall and *PV* module temperature;
- Wind speed, direction and maximum gust;
- Input d.c. current to the inverter;
- Output a.c. current from the inverter;
- Input d.c. voltage to the inverter;
- Grid a.c. voltage and frequency;

Also, some digital and mechanical meters have been placed to read the power factor of the phase line, the energy consumed by the building and the energy delivered by the inverter.

The system has started operation in June 1996 and monitoring is expected to continue for two years, as recommended by the Joint Research Centre - Ispra Establishment, of the European Community.

6. 1-YEAR OPERATIONAL DATA

6.1 Solar Radiation Data

Figure 2, shows the average monthly solar irradiation incident on the horizontal plane and on the array plane. Readings were taken using calibrated Li-Cor and Matrix silicon cell-based pyranometers for the horizontal and inclined planes, respectively. Monitoring of solar radiation has been carried out continuously without any interruptions.

6.2 System Performance

Table 1, shows the monthly number of operational hours and the monitoring fraction MF, as well as the final yield Y_f of the system and the system efficiency η_f.

The mean monthly performance ratio *PR*, defined as the ratio of the useful output energy to the total in-plane solar irradiation, is given in Figure 3.

The system did not operate for some time in September, the whole month of October and the first five days of November. The calculation of the performance ratios of Sep. 96 and Nov. 96 are based on the actual number of operational hours and the corresponding available solar irradiation.

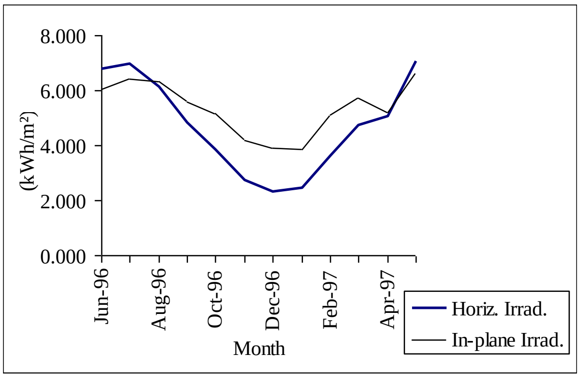

Figure 2: Global solar irradiation on the horizontal and the array plane (Jun. '96 - May '97).

Table 1: Monthly monitoring hours, final system yield and efficiency (Jun. '96 - May '97)

Month	Hours	*MF*	Y_f (kWh/kWp)	η_f (%)
Jun. 96	720	1	4.15	7.4
Jul. 96	744	1	4.16	7.0
Aug. 96	744	1	4.17	7.1
Sep. 96	302.75	0.42	3.62	7.0
Oct. 96	0	0.00	0	0
Nov. 96	600	0.83	2.85	7.4
Dec. 96	744	1	3.00	8.3
Jan. 97	744	1	3.02	8.5
Feb. 97	672	1	3.96	8.4
Mar. 97	744	1	4.32	8.2
Apr. 97	720	1	3.68	7.6
May 97	744	1	4.25	6.9

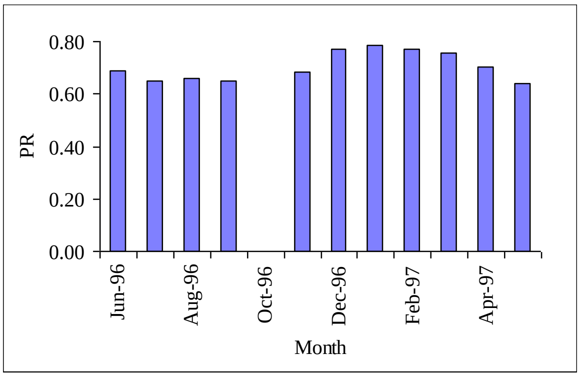

Figure 3: Mean monthly performance ratio of the *PV* system (Jun. 96 -May 97).

6.3 Performance of Inverter

The inverter was struck by lightning during autumn 1996 and this paralysed the system for 53 days, as it had to be sent to the manufacturer for repair. Proper earthing had considerably diminished the damage done to the inverter.

At other times, the inverter stopped due to high grid voltages and variations in grid frequency beyond the pre-set limits.

7. COMPARISON BETWEEN A STAND-ALONE *(SA)* AND A GRID-CONNECTED *(GC) PV* SYSTEM IN MALTA

A brief comparison between the performance of a *SA PV* system [2] and this *GC* system shows that *GC* systems have greater outputs but higher susceptibility to failures, mainly due to the inverter. It is hoped that in the future, this problem would be resolved as the reliability of inverters increase.

The *SA* system operated for 100% of the time of testing of 2 years, while the *GC* system worked for 85% of the first year of operation.

Table 2, shows a summary comparison between the *SA* and the *GC* systems. Data for the *SA* system are an average of 2-year monitoring while that for the *GC* system is for one year only.

Table 2: Comparison between the performance of a stand-alone and grid-connected system in Malta.

***PV* system**	***SA***	***GC***
Reference yield (kWh/day/kWp)	5.302	5.345
Final yield (kWh/day/kWp)	1.892	3.744
System Efficiency (%)	3.94	7.62
Performance Ratio	0.37	0.70

REFERENCES

[1] Iskander Yousif, C. (Feb. 1995), *Testing, Evaluation and Optimisation of the Performance of a Stand-alone Photovoltaic System in Malta,* M. Phil. Thesis, Institute for Energy Technology, University of Malta, Triq il-Port Ruman, Marsaxlokk, ZTN 10, Malta.

[2] Iskander, C. and Scerri, E. (Oct. 1995), Performance of a 1.2 kWp Stand-alone Photovoltaic System in Malta, *Proceedings of the 13th European Photovoltaic Solar Energy Conference and Exhibition,* Nice, France, 23rd - 27th October, 1995, pp. 1019-1022.

[3] Iskander, C. and Scerri, E. (Jun. 1996), Performance and Cost Evaluation of a Stand-alone Photovoltaic System in Malta, to be published in the *Proceedings of the Fourth World Renewable Energy Congress,* Denver, U.S.A., 15th - 21st June, 1996.

[4] Scerri, E. and Iskander, C. (Apr. 1994), Hands-on Experience of the Setting-up of a Stand-Alone Photovoltaic Demonstration Project in Malta, *Renewable Energy Int. Journal,* Vol. 4, No. 3, pp. 359-363, 1994, Pergamon Press.

[5] Enemalta Corporation, *Annual Report & Financial Statements 1995,* Church Wharf, Marsa, Malta.

[6] *Guidelines for the Assessment of Photovoltaic Plants, Document B,* Issue 2, June 1990, Commission of the European Communities, Joint Research Centre - Ispra Establishment.

[7] Avallone, E.A. & Baumeister III, T., *Mark's Standard Handbook for Mechanical Engineers,* Mc Graw-Hill, 1987.

[8] Klein, S.A. and Beckman, W.A., *PV F-Chart Software.*

APPENDIX

Calculation of Solar Elevation (ν):

Obviously, on 21st December, the declination of the sun δ, would be equal to the ecliptic of the earth as shown below:

$\delta = 23.45 * \sin\{360*(K + 284)\}/365;$

where, K = Julian day;

Hence, $\delta = 23.45*\sin\{360*(355+284)/365\}$

$= - 23.45°$

The solar elevation ν, can then be found from the equation:

$\sin \nu = \cos \phi * \cos \delta * \cos \omega + \sin \phi * \sin \delta$

where, ϕ = latitude of site

= 35.835 N;

and ω = hour angle.

$= \frac{360}{24} \times (t - 12);$

where, t = true local time, (true solar time), 0 - 24 hrs.;

= local standard time - $c_1 + c_2 + c_3$;

c_1 = 1, for summer time, in countries which add 1 hour;

= 0, for winter time;

c_2 = longitude correction;

$= \frac{4}{60} \times (\lambda - \lambda_s)$ hours;

where, λ = local longitude;

= 14.543 E;

λ_s = standard time meridian;

Hence, $c_2 = \frac{4}{60} \times (14.543 - 15);$

= - 0.030 hrs.

c_3 = equation of time in hrs., from tables in standard textbooks;

c_3 = + 2.0/60, for 21st December

= + 0.033

Hence, at 8:00 a.m., $t = 8 - 0.030 + 0.033$

= 8 hrs.

i.e. $\omega = \frac{360}{24} \times (8 - 12);$

$= - 60°$

Therefore, $\sin \nu = \cos 35.835 * \cos (- 23.45) * \cos (-60) + \sin 35.835 * \sin (-23.45)$

$\nu = 7.984°$.

Calculation of Solar Azimuth (ψ):

The solar azimuth ψ, is found from the equation:

$$\sin \psi = \cos \delta \times \sin \omega / \cos \nu.$$

Hence,

$$\sin \psi = \cos(-23.45) * \sin(-60)/\cos(7.984),$$

$$\psi = -53.35°$$