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PHOTOVOLTAIC SOLAR ENERGY APPLICATIONS IN MALTA

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ABSTRACT

The paper presents the recent developments in the field of solar photovoltaic (*PV*) applications in Malta. The results obtained from testing the first stand-alone *PV* demonstration project with battery storage (Jul. ′93 - Jun. ′95), encouraged the setting-up of the present 1.8 kWp grid-connected *PV* system, which started operation in May, 1996.

Detailed analysis of the stand-alone *PV* system has already been carried out [5, 6, 7, 8], though some basic operational and costing results are described here, for general reference. Moreover, a description of the set-up of the 1.8 kWp roof-top grid-connected system is presented, together with a tentative description of its performance ratio and life-cycle costing.

A possible scenario of the widespread applications of solar photovoltaic grid-connected systems in Malta is discussed. The factors that contribute to its realisation are also analysed.

KEYWORDS

Photovoltaic; stand-alone; grid-connected; performance; yield; life-cycle costing; sensitivity analysis; scenario.

INTRODUCTION

Studies on solar radiation in Malta and solar measuring instruments started in 1965 [1], followed by further analysis of the Maltese radiation climate (1982 -1992) [2, 3]. In between these years, some B.Sc. and B.Eng. final year projects on solar energy applications were made and a research programme on solar thermal systems was carried out at the Austrian-Maltese Research Centre (1981 - 1985) [4].

Recently, increasing awareness and interest in solar energy applications have been felt in the Island, especially in political circles. The concerns about pollution, the need for energy conservation and the possibility of generating electricity from renewable energy sources are all gaining grounds.

Malta is fully dependant on imported fossil fuel for all its energy needs and this makes it susceptible to any changes in the oil market. Furthermore, the consumption of electricity has been rising at the rate of 8% per annum and this is also directly proportional to the gross national product [11]. Besides, the international agreements signed by Malta for the protection of the environment prompts the country to promote the use of solar energy in everyday life.

Studies on *PV* solar energy applications in Malta started in July 1993, with the testing of a 1.2 kWp stand-alone *PV* system with battery storage, used for lighting purposes, at the Institute for Energy Technology [6]. The aims of this project were to evaluate the potential of using *PV* systems under the local weather conditions. After the completion of this work in June 1995, a 1.8 kWp grid-connected photovoltaic system was commissioned in May, 1996.

Roof-top decentralised grid-connected *PV* systems for power production are suitable for use in Malta because most adjacent buildings have the same height, so no shadowing occurs. Also, the roofs are flat, which means that the modules can be placed in any required direction for optimum performance. Moreover, the roofs are not utilised, except for hanging washed clothes, however it is envisaged that this habit would slowly fade away, especially with the young generation who have a quicker lifestyle, tend to avoid going up the stairs and opt for a tumble drier. Obviously, being an island, the cost of land in Malta is so high that it would be almost prohibitive to install large size centralised *PV* arrays.

SOLAR RADIATION IN MALTA

During the period of testing (July 1993 - June 1995), the mean global solar radiation incident on the *PV* array was found to be 5.302 kWh/m²/day and that on the horizontal plane amounted to 4.705 kWh/m²/day. It has been shown that the number of days that have solar radiation less than 1.5 kWh/m²/day did not exceed fourteen days per annum and that the maximum number of consecutive days which receive this amount of radiation or less is three days [7].

PERFORMANCE OF THE 1.2 kWp STAND-ALONE *PV* SYSTEM

The *PV* array was comprised of 20 modules, inclined at 36° to the horizontal, which is equal to the latitude of Malta, and occupying a projected roof area of 9 m². The balance of system (BOS) components, were a battery bank of 2000 Ah capacity, a battery control unit with lightning protection, light sensors and timers and a set of 25, 11 W each, compact fluorescent lights. These lights were automatically switched on at night [5].

The system was monitored for two years, according to the guidelines for analytical monitoring set by the European Community to test *PV* systems [12]. A portable weather station, solar pyranometers, an automatic data-logging system and back-up mechanical counters were used for monitoring.

In *PV* studies, the most relevant indicator of the performance of a *PV* system is the Performance Ratio (PR), defined as the ratio of the final yield to the reference yield [12]. The average performance ratio for this system was 0.37, with peaks of 0.5 in winter and 0.26 in summer, as shown in figure 1.

Lower performance ratios in summer were mainly caused by [6]:

1. Elevated operating temperatures of the *PV* modules (50-60 °C) and this causes an efficiency drop of about 10%.
2. Disconnection of the *PV* array from the batteries, once the battery control unit sensed that the batteries had reached full charge and this could happen quite early during the day, in summer.
3. Ageing of the batteries had also lead to further lowering of the PR.

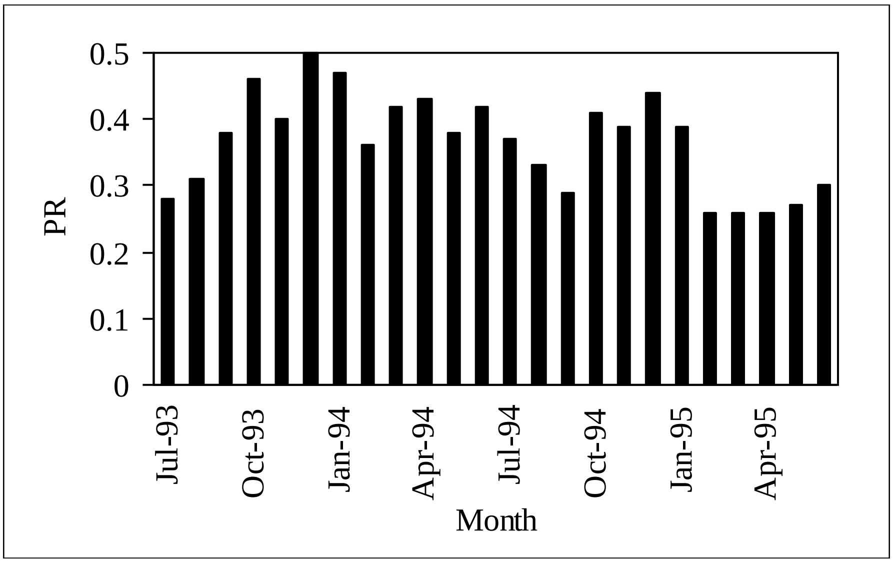

FIGURE 1: Mean monthly performance ratios of the 1.2 kWp stand-alone *PV* system.

The final yield of this system was found to be 1.89 kWh/kWp/day. On the other hand, the *PV* array yield amounted to 3.04 kWh/kWp/day. The difference between the two values is considered to account for the system losses, mainly encountered in the charge/discharge energy efficiency of the batteries, which was found to be 62.2%.

Other studies revealed that dust accumulation during summer does not account for more than 2% drop in *PV* array yield, which implied that washing of the *PV* modules was not essential. However, it has to be stressed that the inclination of the modules should be adequate to allow self-wash by rain during the winter season. The best inclination for maximum annual energy collection is known to be equal to the latitude of Malta of 36° and this is quite enough to facilitate the draining of dust from the modules by rain.

Wind speeds above 2 m/s reduce the operating temperature of the *PV* modules. This is clearly shown in figure 2. Clear days in the hottest months of July and August 1993 and 1994 were chosen. Fifteen-minute averages between 11:00 and 13:00 were used to plot these curves. The temperature difference between the modules and the ambient decreases by almost 6 °C between wind speeds of 2 and 4 m/s [7].

By using linear regression, an empirical equation that related the power output to solar radiation incident on the *PV* modules was computed from 730 days of data. This equation can be used to find the required nominal power of the *PV* array, P_{nom}, for other stand-alone systems in Malta:

$$EA/P_{nom} = 0.675\ IA, \text{ with coefficient of determination } R^2 = 0.98. \qquad (1)$$

where, EA = the array output energy in kWh;
P_{nom} = nominal power of the *PV* array in kWp;
IA = Solar radiation incident on the *PV* array.

It is to be noted that *EA* is the output energy to be expected from the modules. However, for stand-alone systems, only about 65% of this energy will be available for end use, due to battery and other system losses.

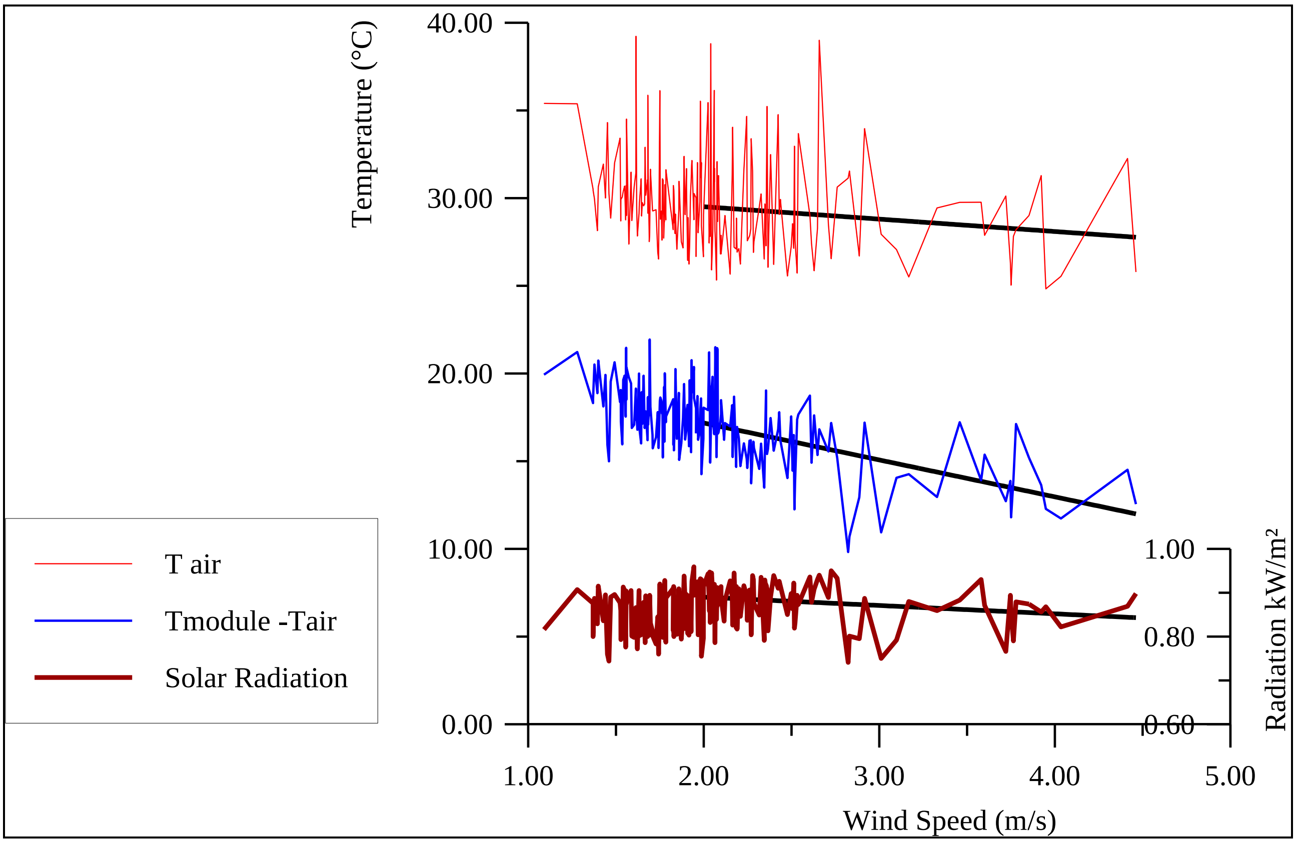

FIGURE 2: Ambient temperature, difference between ambient and *PV* module temperature and solar radiation vs. wind speeds between 11:00 and 13:00, for clear days in July and August, 1993 and 1994.

The life cycle cost of one unit of electricity was found to be Lm 0.87 for a system lifetime of 20 years and battery lifetime of 3 years. By carrying out a sensitivity analysis, it was shown that the cost of a unit of electricity is highly dependant on the energy output of the system, as shown in figure 3 [8]. The performance of the system can be greatly improved by eliminating the batteries, which account for most of the losses.

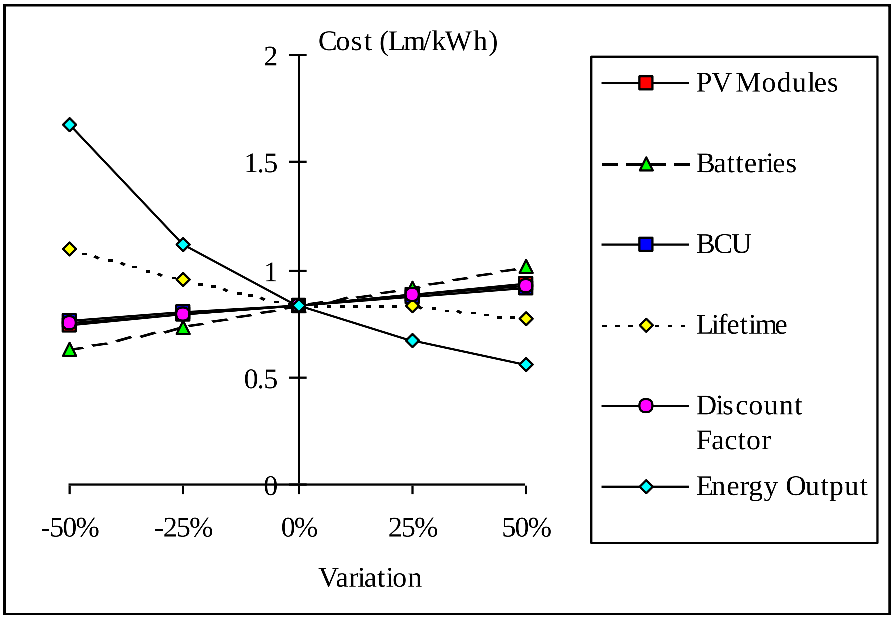

FIGURE 3: Spider diagram of the variable parameters used in the life cycle costing.

An alternative to energy storage in batteries is to interface the *PV* system with the national electricity grid. Grid-connected *PV* systems have the ability to supply electricity at the site, thus reducing transmission losses and overloading during the day. Moreover, any excess units can be fed into the grid. The cost of a unit of electricity generated from a grid-connected system is lower by a factor of at least 7, when compared to a similar stand-alone *PV* system.

Based on these conclusions and aiming at further studies on the performance of grid-connected systems, a 1.8 kWp roof-top grid-connected *PV* system was set up at the Institute for Energy Technology. Studies will be carried out on its performance, its interface with the grid, the optimisation of energy flow and life-cycle costing. Consideration will also be given to energy and load management, supply/demand and roof area/cost ratios. This system is now fully operational and is monitored according to the guidelines set by the European Community for analytical monitoring of *PV* systems [12].

SET-UP OF THE 1.8 kWp ROOF-TOP *PV* GRID-CONNECTED SYSTEM

Thirty, 60 Wp Solarex modules, were connected to form 5 strings, distributed in two rows. Each string contained six modules connected in series. The cables from the five strings were passed from the roof to a control, which contained circuit breakers, over-voltage protection, blocking diodes and earth protection. The total current was then passed, through another circuit breaker, to a 1.8 kW inverter, type SMA PVWR 1800S and from there, onto the grid.

The inverter works on MOSFET/IGBT technology that operate at a switching frequency of 20 kHz. This allows the forming of the sinusoidal 50 Hz grid current with very low non-linear distortion factor and enables the application of a very small light-weight transformer. The inverter is self-commutated, which means that it does not consume reactive power and satisfies all the operation and safety criteria listed below:

- Use of MOS-FET and IGBT technology;
- Use of light weight, high frequency transformer (20 kHz);
- Operating efficiency: not less than 82% at 10% loading and not less than 90% at 25% loading;
- Maximum power tracking capabilities;
- Properly tested against “Islanding”.
- Input d.c. voltage is within safe limits;
- Output a.c. voltage is 240 V ± 5 to 10%; 50 Hz ± 1 Hz, single phase;
- Master/slave capabilities for possible future expansion of the system;
- No harmonic distortion and power factors of at least 0.99 at all loads;
- Properly protected against distorted harmonics due to multiple zero crossings, as may be the case in industrial areas;
- Properly protected against over-voltage or other irregularities that could occur from the side of the grid;
- Isolation protection between d.c. and a.c. sides.
- Ability to store the following data for further transfer to a personal computer:
    - ⇒ Input d.c. voltage
    - ⇒ Output current
    - ⇒ Grid voltage
    - ⇒ Output power
    - ⇒ Daily number of hours of operation
    - ⇒ Total daily energy
    - ⇒ Frequency

- ⇒ Minimum/Maximum values (day/week/month)
- ⇒ malfunctions (diagnosis with date and time)
- ⇒ Switch on and off times

- The inverter has an RS232 serial interface.
- Guarantee of at least 3 years;
- Guarantee of availability of spare parts.
- Easily configured to work on a 3-phase system.

In this system, data is gathered every ten seconds by a micro-processor and average outputs are stored every fifteen minutes. An on-line facility is also available to check the operation of the system. Solar radiation, air temperature, humidity, wind speed and direction, rainfall and *PV* cell temperature are also recorded. The system will be monitored for two years according to the guidelines set by the Joint Research Centre - Ispra Establishment [12].

COSTING OF THE 1.8 kWp GRID-CONNECTED SYSTEM

The performance ratio of grid-connected systems is usually quoted as 80% [13]. As the mean solar radiation on the *PV* array plane in Malta is 5.302 kWh/m²/day, the output of this system would be expected to be 4.24 kWh/kWp/day, or in other words, a total of 2785 kWh/annum.

The capital cost that was spent on this system is given in Table 1:

TABLE 1: Capital required to build a 1.8 kWp grid-connected system (prices of 1995).

Component/Service	Cost (Lm)
PV Modules	4500
Inverter with micro-processor	800
Control Box	200
Steel, beams, trunking, cables, circuit breakers, sealants, paint, stainless steel bolts and nuts, labour, welding, etc...	500
Total	6000

Life-cycle Costing *(LCC)*

The *LCC* method considers the initial costs and all other future costs or cash benefits, and discounts them to their present value. Moreover, this system allows the breaking down of costs, which enables one to carry out a sensitivity analysis study, that analyses the impact of each of the parameters involved in the *LCC*, on the cost of electricity.

The main equation of the *LCC* is [14]:

$$LCC = (C + M + R - P - S)/E \qquad (2)$$

where, LCC = life cycle cost (Lm/kWh);
C = total initial capital (Lm);
M = total maintenance cost (Lm);

R = replacement cost anticipated for the whole life of the system (Lm);
P = Profit (revenue) from selling the generated electricity (Lm);
S = salvage or scrap value at the end of system life (Lm) and;
E = electricity produced (kWh/annum).

The above values have to be converged to their present values by multiplying them by either of the following factors, as appropriate:

For a fixed amount of money to be paid in *n* years, the present value interest factor is given by [14]:

$$PVIF_{k,n} = \frac{1}{(1+k)^n}; \qquad (3)$$

where, $PVIF_{k,n}$ = present value interest factor of one unit of money at a discount rate k at year no. n.

For an annual recurrent expenditure, the present value interest factor annuity is given by [14]:

$$PVIFA_{k,n} = \sum_{t=1}^{n} \frac{1}{(1+k)^t};$$

$$= \frac{1 - \frac{1}{(1+k)^n}}{k}. \qquad (4)$$

In order to choose a suitable value for the discount rate *k*, it would be necessary to know the highest rate of return - known as the nominal discount rate, *m* - on the money invested, had it not been spent on the project. This was taken as equal to the maximum interest rate charged by the local commercial banks of 8.5%. Also, the inflation rate *i*, during the initial year - known as year no. zero - has to be defined. This was given by the Central Bank of Malta as being 3.98% for 1995 [15]. The net discount rate can then be calculated from the equation [14]:

$$(1 + k) = \frac{1+m}{1+i}; \qquad (5)$$

$$k = 4.3\%$$

As for the life-time *n*, of the *PV* modules and balance of system components, they were taken as follows:

PV modules & structure = 20 years;
d.c./a.c. inverter = 10 years;

The salvage (scrap) value of the system was considered to be 80% of the cost of the *PV* modules. Maintenance costs were taken as a constant recurrent cost of 0.5% of initial capital and the selling cost of electricity to the grid was taken as an average of 2.8 cents/kWh.

Table 2 shows the life cycle costing analysis for the 1.8 kWp grid-connected system. The cost of a unit of electricity was found to be 11.8 cents/kWh, however, larger systems give lower costs of electricity. It is to be noted that in this table, no social costs were included.

According to Hohmeyer [16], the social costs could be evaluated to be equivalent to 3.9 cents/kWh. By repeating the life cycle cost analysis, and using the adjusted prices of conventional electricity, as (2.8 + 3.9) cents/kWh, the cost of a unit of *PV* electricity drops to 7.7 cents/kWh as compared to 6.7 cents/kWh from fossil fuelled power stations.

Moreover, this system would save 2.6 tons of CO_2 per annum and 1.1 Tonnes of Oil Euivalent (TOE) per annum, as shown in Table 3. Also, it is envisaged that the use of *PV* grid-connected systems will promote energy conservation, since every unit of electricity saved would render a revenue to the owner.

Sensitivity Analysis

In sensitivity analysis, a parameter is varied by a certain percentage about its present value, while keeping all the other parameters constant. The LCC is repeated based on the new varied parameter and a new price for electricity is found. Using these results, a spider diagram can then be constructed to show which parameter affects the cost of electricity most. The information gained can then be analysed.

TABLE 2: Life cycle costing for a 1.8 kWp grid-connected *PV* system.

Column No.	**1**	**2**	**3**	**4**	**5**
Item	**Year**	**Cost (Lm)**	***PV*IF**	***PV*IFA**	**P.V. (Lm)**
					(2x3 or 2x4)
1. Capital and Installation					
PV Modules	0	4500	1		4500.00
Structure	0	200	1		200.00
Cables, ties, pipes, beams, labour, etc..	0	500	1		500.00
Inverter	0	800	1		800.00
TOTAL					**6000.00**
2. Operation & Maintenance	1...20	30		13.2363	397.09
3. Replacement of inverter	10...20	800	0.6564		525.11
4. Revenue					
Sales of electricity	1...20	77.98		13.2363	1032.17
5. Salvage value					
80% of cost of modules	20	3600	0.4308		1551.02
Total LCC (Items 1+2+3-4-5)					**4339.01**
Annuity = Present Value/*PV*IFA		4339.011		13.2363	327.81
Cost/kWh = Annuity/E	**E = 2785 kWh/annum**				**0.118**

Figure 4 shows the spider diagram for this system. It is clear that this system is most sensitive to the final energy output of the system, or in other words, to the performance ratio. This calls for a continuous optimisation of the individual efficiencies of the BOS components. Also, the spider diagram confirms the fact that a life-time of 20 years is reasonable for use in economic evaluation of *PV* systems. Higher values of life-time do not affect the cost of electricity much and would only render the job more tedious. The cost of the *PV* modules take up to 75% of the total cost of the system, as shown in Table 1. Reduction in their price would definitely bring the cost of electricity down. Use of cheaper thin-film *PV* modules rather than crystalline silicon cells could be considered.

TABLE 3: Calculation of savings in CO_2 production and use of fossil fuel, as a result of using the 1.8 kWp grid-connected *PV* system.

Description	Calculation	References
Generated units of electricity in Malta	769,922,400 (1994)	[17]
Net units sold	596,390,644 (1994)	[17]
Ratio	0.77	
Units produced by *PV* system	2785 kWh/annum	
Units that should have been produced at power stationto produce these units	2785/0.77 = 3595 kWh/annum	
CO_2 production	726 tons/GWh_e	[9]
Amount of CO_2 saved	3595 x 726/1000000 = **2.6 tons/annum**	
Conversion efficiency of power station	0.2	
Units that should have been produced to generate 2785 kWh	2785/0.2 = 13925 kWh/annum	
Equivalent saving in fuel (TOE/annum)	13925/12600 = **1.1 TOE/annum**	1 TOE = 12600 kWh

Other similar projects have been submitted through different financing programmes such as:

- The Italo-Maltese Protocol;
- The Fourth Framework Programme;
- The World Solar Summit Process.

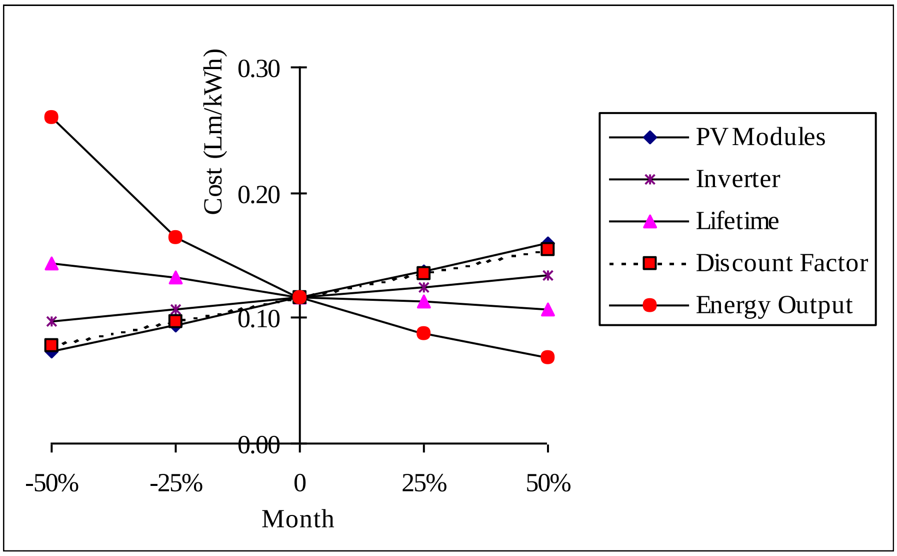

FIGURE 4: Spider diagram of the varied parameters involved in the LCC.

SCENARIO OF *PV* APPLICATIONS IN MALTA

Based on the above information, a scenario for the possible dissemination of grid-connected systems in Malta can be presented as follows:

1996 - 2000 Building of small roof-top grid-connected domestic pilot projects in the capacity of 1 - 10 kWp and large systems for desalination and other

applications, for a total installed capacity of 200 kWp. Such a capacity would produce about 300 MWh/annum, thus saving the environment at least 290 tons of CO_2/annum [9]. Moreover, using the value of 20% as the efficiency of electricity production in Malta, this capacity would save 123 toe/annum.
Continuation of testing and monitoring of selected *PV* systems.
Training of technical personnel and students.

2000 - 2005 A five-year programme to install mixed roof-top, *PV* roof integrated and *PV* cladding systems, for a total capacity of 500 kWp, in residential areas, thus decreasing emissions of CO_2 by a further 725 tons/annum and saving 307 TOE/annum [9].
Installation of *PV* systems in existing and new buildings, using a.c. modules;
Building of grid-connected systems in industrial estates and grid support stations through embedded generation at selected sites.

2005 - 2010 Implementation of laws to include solar *PV* systems in the design stage of all new buildings;
Further implementation of solar *PV* projects on a larger scale.

Such a scenario cannot be realised without the full support of the government, politicians and the public utility. Photovoltaics has become a mature industry with a world total *PV* sales of 88 MWp (1995), which is double the sales of 1989 [10]. The costs are still high due to the manufacturing techniques, low cell efficiency and demand for *PV* modules. Nevertheless, *PV* modules have proved to be economical in many remote applications and for cases, where grid extension is required for more than 5 km, to a site that consumes more than 35 kWh/day. Moreover, the improvements in cell efficiency and reductions in manufacturing costs have brought the costs down by a factor of 5 since 1978 [11] and this is expected to continue for the coming years [11].

The factors that would contribute to the development of this sector in Malta are:

- Setting up of a national renewable energy plan;
- Formation of a national renewable energy body to foster the national renewable energy plan;
- Formation of a technical body to certify the quality of imported or locally manufactured modules and inverters, according to the national and international operating standards;
- Exemption of *PV* modules and their related BOS components from the value added tax (VAT);
- Inclusion of a carbon/pollution tax in the energy and petroleum sector;
- Subsidising the national renewable energy plan from the carbon tax;
- Changing the energy legislation to allow grid-interfacing;
- Subsidising and offering of soft loans to citizens who wish to install *PV* grid-connected systems;
- Purchasing of extra power produced by *PV* systems by Enemalta at the same rate as the selling price of conventional electricity;
- Encouraging the local manufacturing of *PV* modules and related electronic components.

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