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Complete Engineering and Economics of Solar Photovoltaic Hybrid Power Systems

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Abstract
The objective of this article is to present a new numerical approach for a complete design, optimum sizing, cost estimation (capital & $/kWh) and also evaluating the performance of solar photovoltaic/battery/diesel hybrid power systems.

The world-wide demand for solar photovoltaic energy systems has grown steadily over the past 15 years. The need for **reliable** and **low cost** electric power in remote areas of the world is the primary force driving the world-wide photovoltaic (PV) industry. For a large number of applications, PV technology is almost the best and economical option. Typical applications of solar PV in use today include stand-alone power systems for remote located facilities and residences, grid-connected PV systems for residential and commercial buildings that are already connected to national electricity network and finally solar PV hybrid power systems for isolated communities and facilities. The latter combines PV array with a conventional electricity generating unit such as diesel generator. Solar photovoltaic energy systems have many advantages. In fact they are modular and silent, they have no moving parts, they require low maintenance, and produce no emissions.

Significant growth in demand for solar PV systems is expected to occur in the countries of the developing world to help meeting the basic electrical needs of billions of people without access to electricity.

In our research group we have developed a new numerical program, which has many features including size optimization, cost calculation and performance prediction of any type of solar PV system. This program also enables us to see the effect of non-technical factors such as inflation rate, discount rate, mortgage rate, etc. on the capital and electricity cost of the solar PV system under investigation.

A method has been developed to predict a day-by-day performance of all components integrated in a solar PV-hybrid power system. Hourly average solar radiation data from the site for generating unit and the anticipated load data are used to evaluate the performance of the components in the system. Such performance evaluation is useful for optimizing the size of the components in the system. This method will also help us to perform economical analysis of the entire system over the system's lifetime period.

The system under investigation is a solar PV hybrid power system, in which the integrated components are PV array, a battery bank for backing up the system and a diesel generator set for

supporting the battery bank. State of charge (SOC) of batteries is used as a measure for evaluation of system's performance. The operation time of diesel generator is determined by the SOC of batteries. In this method it is shown that the usage of PV electricity is maximized, the size of the components is optimized and the amount of fuel used for the diesel generator is minimized and no electricity is wasted.

Introduction

The usage of renewable sources of energy which produce less (and in some cases no) pollution are considered more seriously. Rapid advances in solar photovoltaic technologies have brought good opportunities for the utilization of solar PV power. Moreover, the economic aspects of these technologies are now sufficiently promising to also justify their use in small-scale stand-alone applications for users who are not connected to national electricity grid.

Solar PV energy has attracted in the past decade lots of attention and the experts in this field believe that this energy has a promising future. The main characteristics of this renewable energy are followings: the fuel is free, technology is mature and almost world wide available and it has many other advantages like modularity, low maintenance requirements, high durability and also they can easily be connected to the utility grids.

A rooftop mounted photovoltaic system is one of the applications of solar PV systems that has attracted lots of interest among the people of North America, Europe and Japan. The generation of electricity by this system is attractive because:

- Generation is on-site. This results in reduction of transmission costs and transmission losses;
- The cost of roofing tiles can be eliminated by using mounted PV systems instead;
- There is no need for additional land for power generation;
- Visual impacts are limited.

Using photovoltaic energy has particular benefits for industrialised countries. These benefits include employment, emission reduction and security of supply. The only factor hindering the growth of utilization of PV in this sector is the high capital cost. Thus, developing a method to reduce the cost will help increasing utilization of PV systems.

Another sector that photovoltaic can have a major contribution is in generating electricity for people living in isolated areas, those who have mini diesel grid, for example, and are not connected to national electricity network. The main factors favouring photovoltaic technology in this sector result from:

- The high costs of conventional energy sources in remote locations
- The loss of a scale-economy effect, which means specific costs of small photovoltaic systems are not much higher than those of larger photovoltaic systems.
- Price of fuel, fuel transportation and spare part supplies.

The major factors inhibiting the photovoltaic technology in this sector include high initial costs, lack of skilled manpower, lack of good quality data and social acceptance. Thus, developing an accurate sizing method for reducing the cost of system is appropriate.

Another PV application sector is electrification of remote located communities, those who are without electricity at all. According to United Nations, there are 2 billion people living on the earth that have no access to electricity. Solar PV energy can make a significant contribution to improving the quality of life of innumerable small communities, especially in rural areas, by helping them to meet their basic needs such as health care and education. Photovoltaic electricity can also provide the opportunity for remote communities to meet essential water pumping, refrigeration and communication. The main factors favouring photovoltaic technologies in remote areas result from:

- The high costs of conventional power sources, which are strongly affected by remote locations;
- The loss of the scale-economy effect and
- The relatively high price of fuel transportation and of the supply of spare parts.

In this sector, like the other sectors, the high capital is a barrier hindering the growth of use of PV systems and developing a method for cost reduction is appropriate..

High cost of PV electricity

The development of solar PV electricity suffers from high capital cost. However, there is an extensive range of applications where the PV systems are the best and economical option for electricity supply. These are usually stand-alone systems, and exploit the following advantages of solar PV electricity.

- There are no fuel costs or fuel supply problems
- The equipment can usually operate unattended
- It is very reliable and requires little maintenance

These advantages make solar PV the greatest opportunity of electricity generation for billions of people throughout the world without electricity. However, there are some technical and non-technical factors hindering utilization of PV as the high cost of photovoltaic systems is capital intensive.

Although fuel of solar PV generators is free, but price of PV electricity is far above the price of electricity from conventional fossil fuel power plants. In some countries this is more than double. And also PV electricity is the most expensive amongst the other renewable electricity prices. This has been clearly shown in Figure 1.

This high capital cost is affected by some technical factors such as efficiency, technology, reliability, location, orientation, tilt, as well as some non-technical factors, which are often overlooked.

One of the important factors, which directly affect the PV electricity cost in positive way is correct system-sizing mechanism of the system's components. Over-sizing of components in PV hybrid system make the system, which is already expensive, more expensive, under-sizing on the other hand makes the system less reliable. Thus optimum sizing gives two benefits to the system a) being economical, b) being reliable.

In this approach we try to minimize the cost of hybrid power system by optimizing the size of components in PV system and investigate the effect of some non-technical factors on these costs. In order to make sure that this does not result in poor performance, we try to evaluate the performance of the system to see whether the PV system is capable of producing a reliable electricity supply.

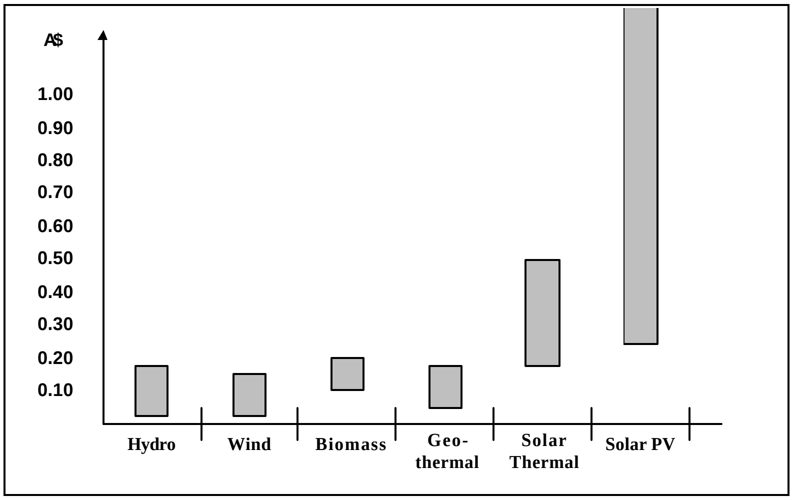

Figure 1

System Configuration

The block diagram for the system under investigation is shown in Figure 2. The system is designed to supply a **reliable** and **low-cost** electric power for a remote located and isolated community. The system consists of a PV array, storage batteries, and a backup generator. The size of PV array is so that is able to supply the entire load during three months of summer period. In other words, the daily production of electricity by PV array in a typical summer day is equal to the daily electricity required by the load. During the day when the generated power by PV array exceeds the demand, PV array starts charging the batteries.

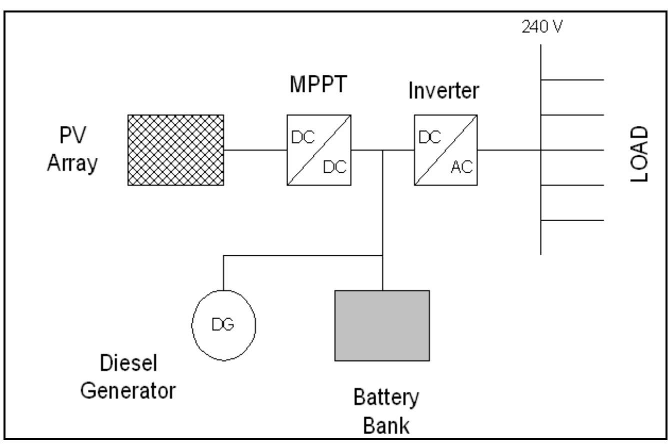

Figure2. The single line diagram of the PV hybrid system

Why PV hybrid system

Technically a system which is entirely dependent on renewable sources can not be reliable electricity supply, especially for isolated loads in remote areas. This is because the availability of the renewable sources can not be ensured. Therefore, solar PV hybrid systems, which combine conventional and renewable sources of energies, are a better choice for isolated loads. A solar PV hybrid power system is expected to:

a. Satisfy the load
b. Minimize the costs
c. Maximize the utilization of renewable sources
d. Optimize the operation of battery bank, which is used as back up unit
e. Ensure efficient operation of the diesel generator

Load

In this investigation and simulation we have assumed that the load requires an average of 18 kWh every day. To simplify the calculations we assume that the amount of electricity required by the load remains constant over the year.

As the size of PV array is optimum so the excess power will not cause any overcharging of the batteries, thus, there is no need for a dummy load to be integrated in the system. Batteries will supply power during the nights and cloudy days. Every day the backup diesel generator operates for some hours, depending on season and month of the year, to charge the batteries. The number of hours of operation of diesel generator depends on state of charge (SOC) of batteries and is determined accordingly. In order to minimize the fuel cost and avoiding wasting electricity, the diesel generator keeps charging the batteries until a specified upper limit for the battery voltage is reached. At this point the backup generator will stop charging the batteries

Size of PV array

We have adopted a numerical sizing procedure in which the PV array is the main electric power generator. Our system design is based on the seasonal energy balance between the radiation and the load. In order to avoid wasting PV electricity the size of PV array is determined based on the summer radiation data. This means that during three months of summer period the load is covered fully by the PV array. Obviously the PV energy is not able to supply enough power during the other seasons. Battery bank is there to support the PV array and the diesel generator is to backup the battery bank.

The energy deficit is covered effectively by a diesel generator. The radiation data for the site, together with the panel orientation are used to determine the incident solar radiation on the panel for a typical day in summer months.

The number of series connected modules is determined by the DC operating voltage. As the modules are used for battery charging we are more interested in the current at a good battery charging voltage under normal operating conditions.

The number of parallel strings is directly related to a) the current requirement for the load I_L, b) the nominal current I_P which is required from the PV array when working at its maximum power point and irradiated by the standard AM 1.5 radiation at 1 kW/m^2 and the nominal current supplied by an individual PV modules. We can also introduce a sizing factor SF, which can be used to oversize the amount of current available from the array.

Size of battery bank

The daily and seasonal charge deficits have to be calculated. It must be ensured that the night and cloudy periods are covered satisfactorily. At the same time, excess energy generated and not used during the sunshine periods must be stored. This analysis determines the daily charge and discharge percentage of the battery that usually can not exceed a given value for the safe operation. The energy balance for the summer periods is set in such a way that the day energy excess is stored effectively to cover the energy deficit during the night and cloudy times.

In this method we determine the size of battery bank based on the number of no-sun days. This depends on the location, where the PV system is installed and differs from place to place. For the sizing of battery bank for the system under investigation we are assuming 5 days of autonomy (no-sun-days). This is worse case that can happen having a 5 consecutive days without sun. Therefore the AH of battery bank should be determined by following equation:

AH = (daily demand x 5 days / system's efficiency) / DC voltage / depth of discharge

Size of diesel generator

Diesel generator is used in the system for following tasks:

- To bring the SOC of batteries to an acceptable level. This can be done by running the diesel generator for 1 – 5 hours every day depending on the size of diesel generator and the climate conditions.
- To charge the batteries when 5 no-sun-days happen. When this case occurs the diesel generator must be large enough to charge the batteries to avoid batteries undercharging.

The size of diesel generator is determined by an experimental formula which is charging the batteries from 20% to 70% in 5 hours.

Calculation Results

Table 1 shows the complete sizing and costing results. Hourly solar radiation and power demand, and a time step of one hour were used in this work. By selecting one hour as a time interval, we were assuming a constant solar radiation and constant power demand during each hour. This assumption does not have considerable effect on the general hourly response of the generating system since hourly average data were used. Since solar radiation and power demand can vary seasonally, more accurate results can be obtained if the study is performed using seasonal data.

The size of each component in this system depends on the kWh/day required by the load as well as the amount of sun energy received by solar array.

Table 2 shows the number of hours per day in each month that the diesel generator has to operate to ensure that batteries remain in healthy conditions and the load receives the electricity needed.

The study results presented in this paper are for one set of system components selected based on the actual solar radiation data available at one specific location to supply the power demand of a community in an Australian remote located place, which is away from national electricity grid. However, the approach can be applied to other locations and applications if and when data is available.

Latitude (S) : 37D32MS(37.53)
Longitude (E): 143D49ME(143.72)

Latitude	Longitude	PSHrs/Year	Spring	Summer	Falls	Winter	Ann-Ave.	World Ave.	PSH (Cal.)	Life time
37.53	143.72	1657.0	5.6	6.8	3.5	1.9	4.5	5.75	6.8	25
B. Eff.	Inv. Eff.	PV-Eff.	Wiring Eff.	Depth of Discharge	PV Siz-Factor	Bat. Siz-Factor	kWh/Liter	Usage (kWhrs) / Day	Size in kW	No. of No SUN
0.85	0.90	0.95	0.98	0.80	1.0	1.0	0.7	18	3.74	5
PV ($/Wp)	Inverter Size (kW)	Inverter cost($/kW)	O&M/kW /year	Inflation Rate	Discount Rate	Mortgage Rate	Factor (X)	Present Worth	Bat.Cost	DG Cost/kW
10.0	3.93	3000	100	0.03	0.1	0-10%	0.936	12.678	150	1000
Pmax (W)	Vmp (V)	Imp (I)	Voc (V)	Isc (I)	Fill Factor	%DG	Voltage	Voltage	Voltage	Fuel Cost $/L
80	17	4.71	21.1	5.13	0.74	0.5	12V? Or	24V	48	1.00
Demand / year	PV&DG / Year	PV / Year	DG / Year	% by PV	% by DG	Angle factor				Elect. Cost $/kWh
6570	6879	3749	3130	57	48	0.85				**2.27**

Table 1 Sizing results

Hrs in Jan	Hrs in Feb	Hrs in March	Hrs in Apr	Hrs in May	Hrs in June	Hrs in July	Hrs in Aug	Hrs in Sep	Hrs in Oct	Hrs in Nov	Hrs in Dec
1	1	2	3	4	4	5	4	4	1	1	1

Table 2 Number of hours per day in each month that the diesel generator has to operate

Performance evaluation

In order to make sure that the system, for which we have conducted the optimum sizing, is able to supply reliable electricity for the load, we have performed a computer simulation for the purpose of performance evaluation. As battery bank is the weakest component in the PV hybrid power system, we have chosen the state of charge (SOC) of batteries as a measure for performance prediction.

Figure 3 shows the every day's peak sun hour, while Figure 4 shows the generation profile of solar PV array. Figure 5 shows the generation profile of the diesel generator. Figure 6 shows the total generation by PV and diesel generator. Figure 7 shows the energy balance and Figure 8 shows the state of charge of battery in one year. In winter, when the least sun shine is available the depth of discharge of the battery bank is just above 60%. The irradiation pattern has been shown in Figure 3.

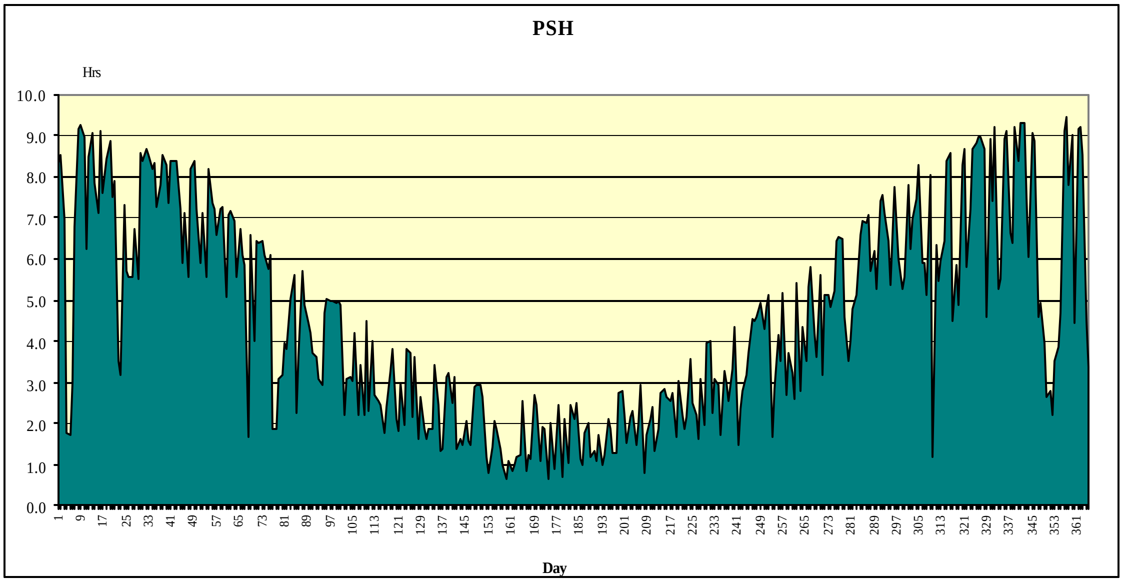

Figure 3 Every day's peak sun hours (PSH) of the location over one year

The power production by the PV array has been shown in Figure 4. It has a pattern similar to the irradiation pattern. This is because that the main factor affecting the power production of PV generator is the irradiation.

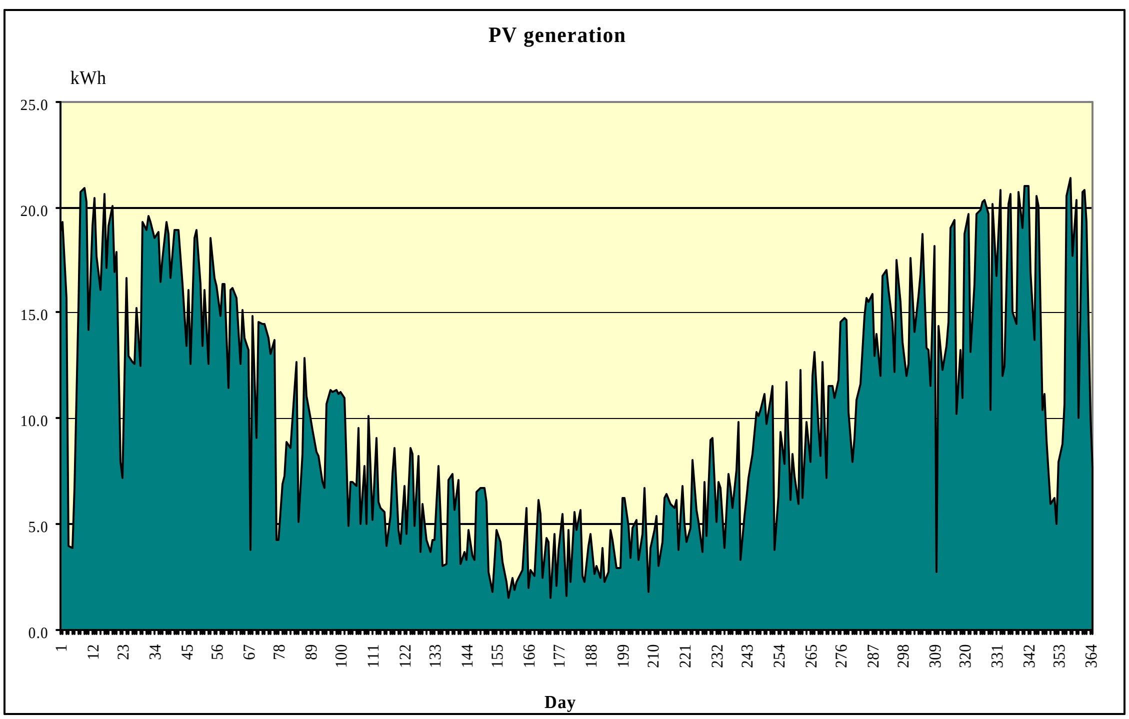

Figure 4 Energy generated by PV array every day over one year

The power production by the diesel generator has been shown in Figure 5.

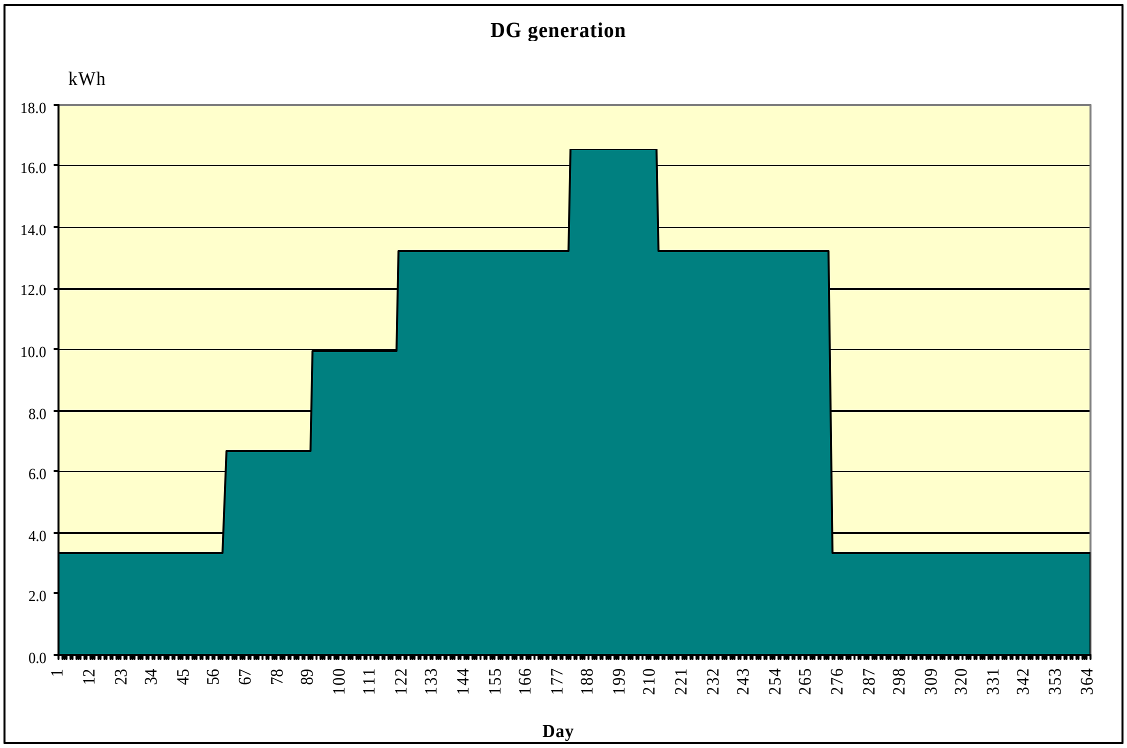

Figure 5 Electricity needed to be generated by diesel generator every day of the year

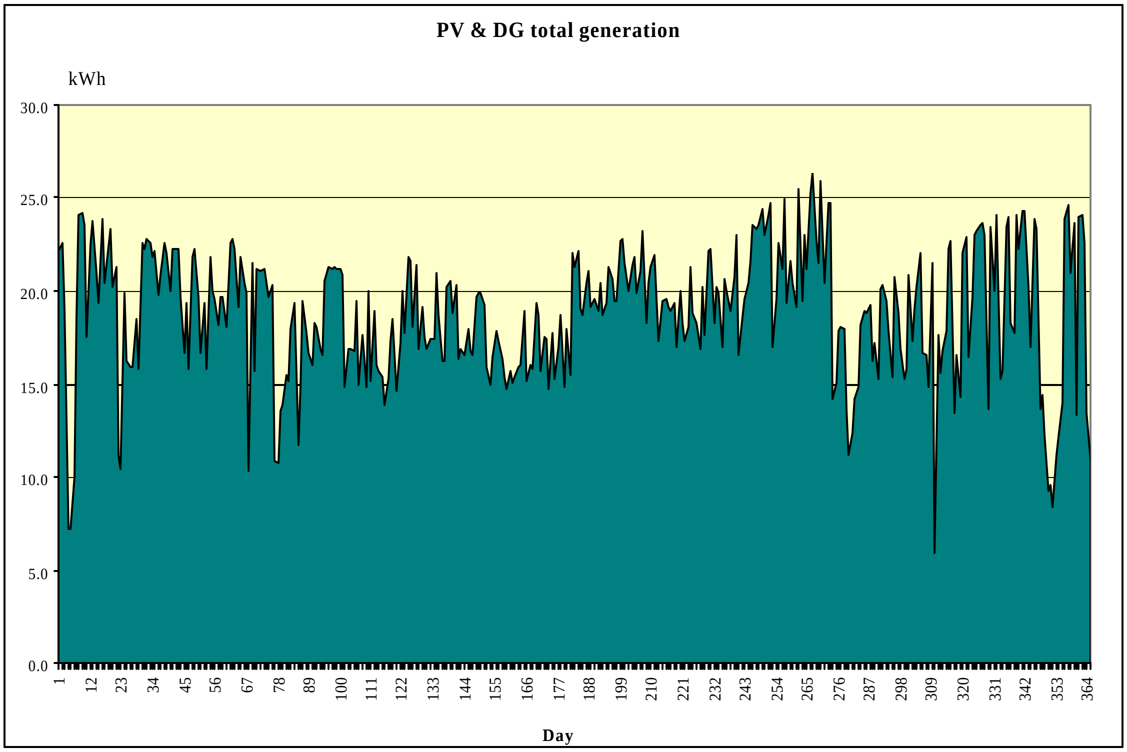

Figure 6 Total generation by PV and diesel generator

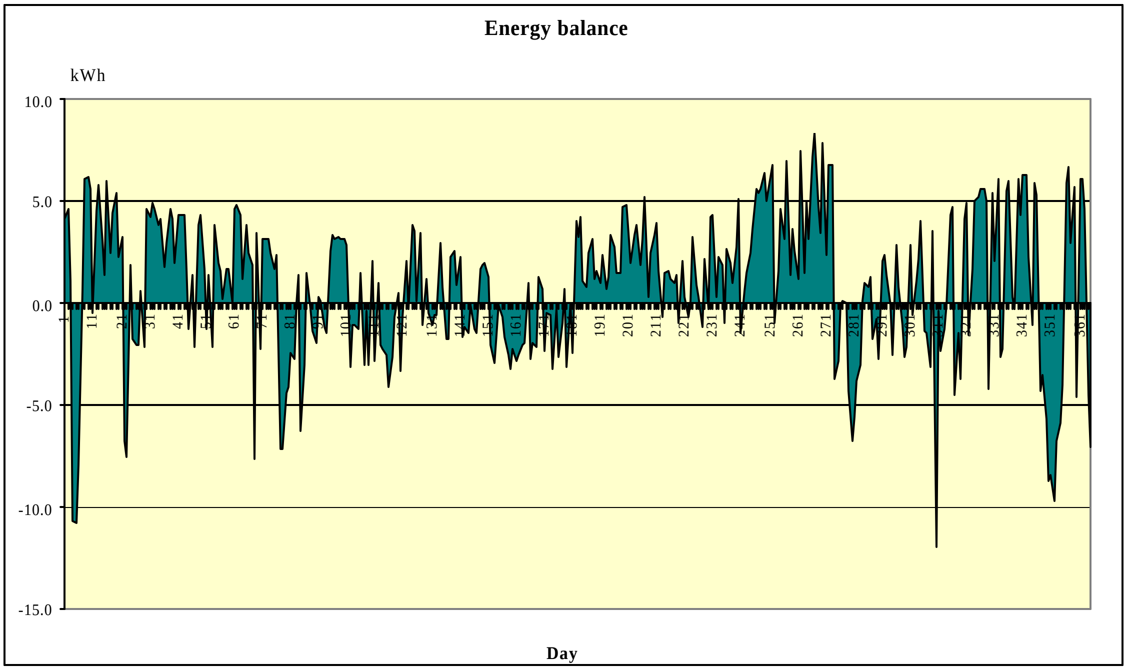

Figure 7 Energy balance, excess and deficit

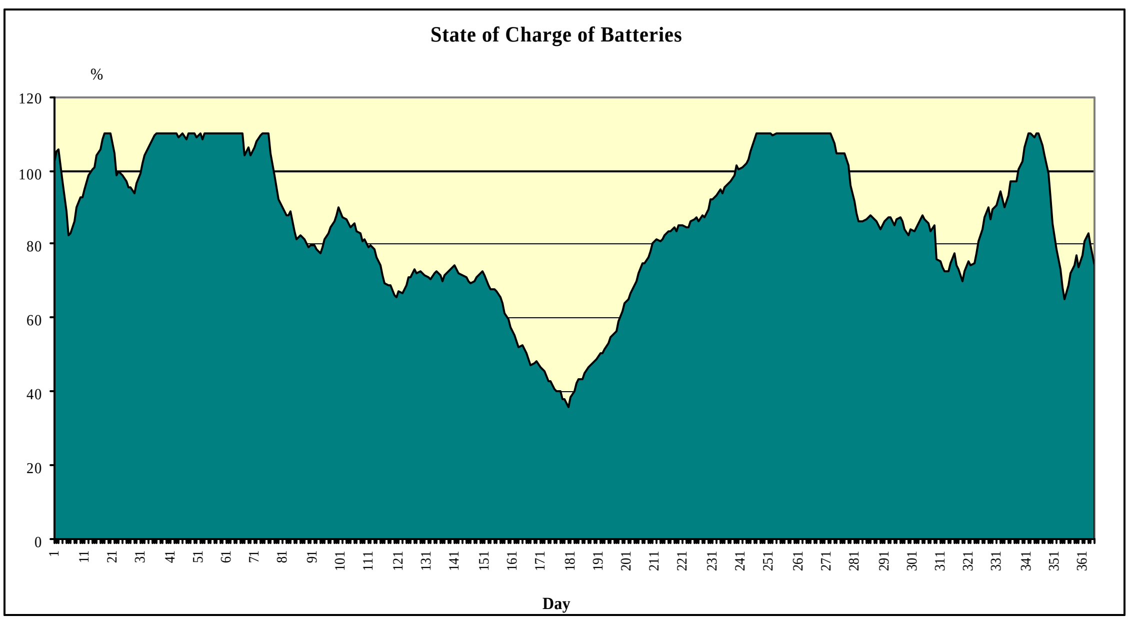

Figure 8. State of charge of the battery bank

Electricity cost analysis

Table 3 shows variation of electricity in terms of interest rate on the money borrowed from a financial institution for installation of photovoltaic system. When money is available and not borrowed from a financial institution and no AGO support is provided, the electricity cost will be A$2.27.kWh as shown in Table 1.

Case 1. No subsidies		**Case 2. AGO subsidies**	A$7,500
Interest rate (%)	0.00	Interest rate (%)	0.00
ANN-PMT	7565	ANN-PMT	7265
Electricity cost $/kWh	**1.15**	Electricity cost $/kWh	**1.11**
Interest rate (%)	1.00	Interest rate (%)	1.00
ANN-PMT	8587	ANN-PMT	8246
Electricity cost $/kWh	**1.31**	Electricity cost $/kWh	**1.26**
Interest rate (%)	3.00	Interest rate (%)	3.00
ANN-PMT	10860	ANN-PMT	10429
Electricity cost $/kWh	**1.65**	Electricity cost $/kWh	**1.59**
Interest rate (%)	5.00	Interest rate (%)	5.00
ANN-PMT	13418	ANN-PMT	12885
Electricity cost $/kWh	**2.04**	Electricity cost $/kWh	**1.96**
Interest rate (%)	7.00	Interest rate (%)	7.00
ANN-PMT	16227	ANN-PMT	15584
Electricity cost $/kWh	**2.47**	Electricity cost $/kWh	**2.37**
Interest rate (%)	8.00	Interest rate (%)	8.00
ANN-PMT	17715	ANN-PMT	17013
Electricity cost $/kWh	**2.70**	Electricity cost $/kWh	**2.59**
Interest rate (%)	10.00	Interest rate (%)	10.00
ANN-PMT	20834	ANN-PMT	20007
Electricity cost $/kWh	**3.17**	Electricity cost $/kWh	**3.05**

Table3. AGO (Australian Greenhouse Office) provides financial support

The variation of electricity cost as a function of mortgage rate on the loan borrowed for installation of PV system has been shown in Figures 9 and 10. Figure 9 shows this variation for the case that the Government does not provide financial support, while Figure 10 shows this variation for the case that the Government provides financial support.

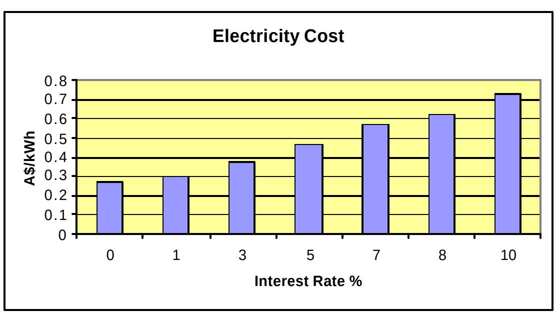

Figure 9

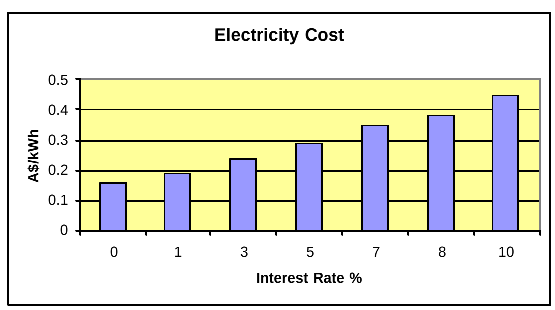

Figure 10

Conclusion and Remarks

An accurate sizing of components of PV hybrid power system has been presented. This paper has referred to the fact that the non-technical factors such as correct sizing, inflation rate, discount rate and mortgage rate have strong effects on the capital and electricity cost of PV hybrid power systems. The correct sizing is important part of designing a hybrid system. Over-sizing the system makes it more expensive and will result in wasting electricity, while under-sizing makes the system unreliable. Therefore optimum sizing is very important. Optimum sizing is important because it ensures minimum capital and electricity cost as well as reliable system. In this investigation we have assumed that the PV array generates in summer the same amount of energy which is needed by the load in a typical summer day. Usage of diesel generator will be minimum in summer. In the other seasons PV array generates less electricity, therefore usage of diesel generator will be more. This arrangement offers all the benefits of PV systems with respect to low operation and maintenance costs, and also ensures that PV electricity is not wasted.

This paper presented an approach for evaluating the performance of PV hybrid power systems. It is a useful tool for predicting the performance of the solar PV hybrid power systems before they are installed. This paper presented a performance prediction method based on the SOC of the batteries. The method developed and presented in this paper can be used for any locations by any applications provided solar radiation data are available and daily electricity consumption are known.

Further work

The further work that will be carried out immediately is the system cost versus benefits of increasing or decreasing the size or the number of each system components in a the PV-hybrid power systems.

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