Design of Low Cost and High Efficiency Smart PV Solar System for Sustainable Residential Home

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***Abstract*—Renewable energy is becoming an essential element when it comes to climate change. The cost of energy storage is one of the main setbacks for sustainable homes. The paper includes important information on designing the PV solar system with energy storage for residential properties. It introduces the priority concept to reduce the battery storage size. The concept reduces the investment cost to make it attractive to homeowners. A case study is included.**

***Index Terms*—Maximum Demand, Smart System, Solar Energy, Sustainable House.**

I. Introduction

Renewable energy technologies play a significant role in reducing the carbon footprints of electrical generation plants. Worldwide policies are being established to promote the spread of renewable energy technologies. For example, Australian government offers incentive to those who install small-scale renewable energy at their properties. The most commonly installed renewable energy system for residential properties is the PV solar system.

The PV solar system occupies the roof of the residential properties and assists the reduction of the electricity bills. The small PV solar system is known as micro-grid for residential properties. The micro-grids generate low power on sunny day. The outputs power ranges between one and tens of kW per property. The system is installed in two forms; grid connected and stand-alone systems [1-5].

The cost of the energy storage prevents large number of applicants from installing the off-grid system. The off-grid system harvests the power during the sunny hours and utilized it during night times. To ensure system reliability and continuous power, large energy storage is required to cater for the household electrical maximum demand. The large system increases cost of the investment. Based on this information, the reduction in energy storage will reduce the cost of the system, making it more attractive to homeowners.

Accurate system sizing requires accurate house loading analysis. The paper contains valuable information on analysing the house electrical maximum demands, the required PV panels sizing and the size of the storage system. The paper introduces the priority concept to reduce the energy storage system. The priority concept is based on house priorities of using the electrical loads and smart technologies. A case study is also included to explain the feasibility of concept.

II. Theoretical Study

As discussed, the theoretical study covers the following aspect of the PV standalone system for residential properties:

- Electrical household maximum demands analysis
- PV panels system sizing
- Energy storage
- Priority concept analysis

A. Maximum Demand Analysis

The maximum demands analysis is required to compute the power required for the following points:

- Operate the installed electrical apparatus
- Cable sizing
- Protection design

The maximum demand will provide the design with the maximum instantaneous power in kW and maximum daily consumption in kWh. The maximum instantaneous power can be computed using equation 1:

$$P_i = P_h + P_n \tag{1}$$

Where

P_i is the maximum instantaneous power in (kW)

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P_n is the starting power of the largest electrical apparatus (kW)

P_h is the maximum standard rated power of the house excluding the rated power of the largest electrical apparatus (kW)

For example, if the house standard operating power is 2kW and the largest electrical apparatus requires 5kW as the start-up power, the maximum instantaneous power is 7kW.

The maximum electrical demands of the house can be computed using equation 2:

$$P_{MD} = \sum_{1}^{M} P_m h_m \tag{2}$$

Where

P_{MD} is the electrical daily maximum demands (kWh)

P_m is the rated power of an “m” electrical apparatus (kW)

h_m is the operating time of the “m” electrical apparatus per day (hours)

M is the number of operated electrical apparatus

B. PV System

For an adequate electrical system, the output of the installed solar PV system shall provide an instantaneous power that exceeds P_i and daily electrical energy that exceeds P_{MD}. The PV solar system consists of the following items:

- Solar panels
- DC switches
- Charger controller, DC-DC converter (if storage is available)
- DC-AC Inverter
- AC distribution boards

To ensure system reliability, the output of the solar panels and DC-AC inverter shall meet the requirements of P_i and P_{MD}. In addition, for a stand-alone system, the PV panels should charge the batteries within the required period.

The battery storage size depends on the house power demands and the number of days that the system should support the house electrical requirements. Equation 3 represents the battery storage:

$$B_{Storage} = P_{MD} \times D \tag{3}$$

Where

$B_{Storage}$ is the battery storage in kWh

D is the number of days

It is worth nothing; this paper uses unity as the value of D. To extend the life of the battery storage, the discharge should not exceed the maximum allowable level of discharge [6]. Equation 4 shows the updated battery storage [6]:

$$B_{Storage} = \frac{P_{MD} \times D}{\eta} \tag{4}$$

Where

η is the maximum allowable level of discharge

The adequate solar array should supply sufficient power for the daily use and ensure the batteries are always full of charge.

Equation 5 represents the PV kWh daily outputs:

$$E_{PV} = \frac{P_{MD} \times D}{L_{PV}} \tag{5}$$

Where

L_{PV} is the losses percentage of the PV panels

C. PV System Layout

Figure 1 shows the layout of PV solar system which consists of PV panels, Charge Controller, Battery banks, DC bus and DC-AC inverter. This layout allows for dual bus house feed (DC and AC loads).

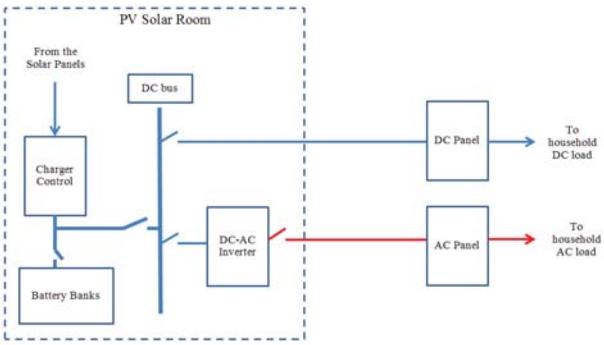

Figure 1. PV solar system layout [8]

The output of the solar panels is fed to the charge controller. Therefore, the PV panels shall be set to suit the maximum input voltage of the chosen charge controller. Equation 6 represents the maximum number of PV panels in series:

$$N_{PV} = \begin{cases} \frac{V_{CC}}{V_{OC}} \\ \& \\ N_{PV} \times V_{OC} > V_{SCC} \\ \& \\ N_{PV} \times P_{PV} < P_{CC} \end{cases} \quad (6)$$

Where

N_{PV} is the number of PV panels in series. N_{PV} is an integer number

V_{CC} is the maximum charger controller open circuit

P_{CC} is the charger controller rated power

V_{OC} is the PV panel open circuit voltage

V_{SCC} is the charger controller start-up voltage

P_{PV} is the single panel maximum rated power

Equation 7 determines if the current charger controller is suitable for the proposed installation. If equation 7 is not valid, the designer has two options:

1. Install another charger controller, or
2. Replace the current charger controller with larger one

$$N_{PV} \times P_{PV} \geq P_{CC} \quad (7)$$

To simplify the design process for the charger controller, the proposed design diagram is shown in figure 2. The case study uses the proposed diagram to choose the adequate charger controller to suite the required system. Equation 8 the maximum number of PV panels in a series array required to support the required maximum demand.

$$N_{PV-E} = \frac{E_{PV}}{P_{PV} N_h} \quad (8)$$

Where

N_{PV-E} is the number of PV panels require to supply the required load as per equation 5

N_h is the number of sun hours per day

The inverter should be able to convert the battery DC voltage into AC and produce an instantaneous power that exceeds P_i.

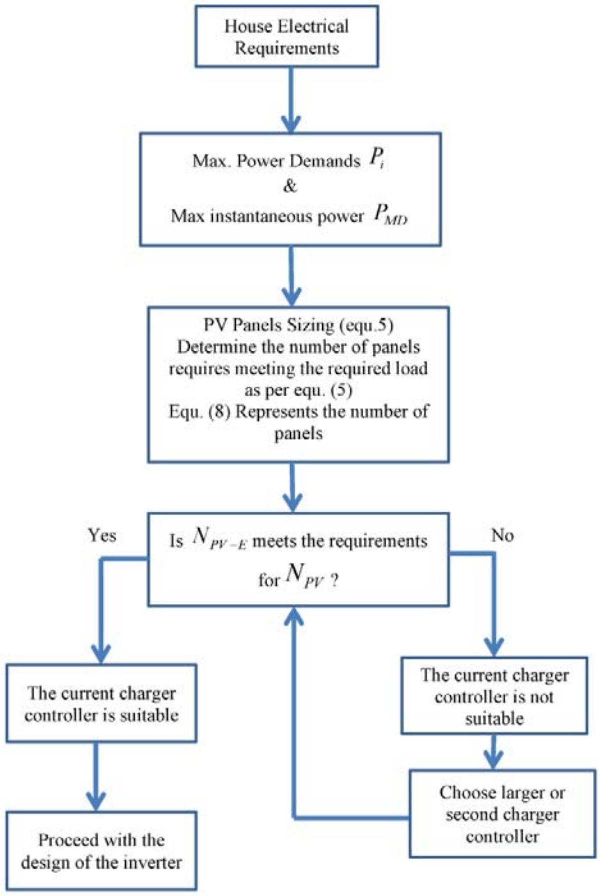

Figure 2. Proposed design diagram

D. Priority Loading

The batteries store the energy generated during sun hours to support the required load during night time. Therefore, the batteries capacity should meet the house electrical load outside sunlight hours. Based on this concept, the home owners play an important role in sizing the battery storage as they govern the night time electrical load. The priority concept is based on designing the system to reduce the size of the required battery storage. The home owners determine the critical night time and set the priority of its operation. Table 1 represents the electrical apparatus and its night priority usage:

The 50/50 means: operating these items during the day will reduce its electrical consumption outside sunlight hours.

The priority list reduces the required electrical consumption outside the sunlight period. This reduces the size of the energy storage required to ensure 100 percent of the house running on solar energy. In addition to the priority list, the house owners can use the shift load concept to further reduce the energy consumption outside the daylight period [7]. Australia is fortune to have larger hours of daily sunlight as shown in figure 3 [8, 9].

TABLE I. LIST OF HOUSEHOLD APPARATUS

Details of electric apparatus	Evening& Night priority	Can night operation be completed during the day?	Can operate using Gas or Wood
Refrigeration	Yes	No	NA
Air-condition	Yes	50/50	NA
Heaters	Yes	No	Yes
Hot water	No	Yes	Yes
Washing machine	No	Yes	NA
Dryer	No	Yes	NA
Stove and oven	Yes	50/50	Yes
Toaster	Yes	No	NA
Kettle	Yes	No	NA
Lights	Yes	No	NA
Televisions	Yes	No	NA
Vacuum Cleaner	No	Yes	NA
Chargers	Yes	No	NA
Fans	No	Yes	NA
Motors	No	Yes	NA
Miscellaneous	No	Yes	NA

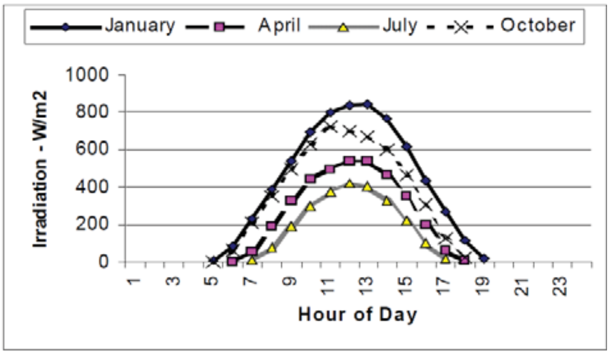

Figure 3. Solar hourly energy distribution in Australia [9, 10]

Figure 3 shows that July represents the worst case scenario for sizing the PV solar system. July represents winter period in Australia. Therefore, air-condition is not required and for heating, the owners can rely on gas or timber for heating. Furthermore, the electric motor for the swimming pool, if applicable, requires running for shorter period. This automatically reduces the electrical power consumption of the house.

E. Priority Loading Battery Sizing

The following steps will be followed to compute the battery storage requirements as per the priority loading concept:

1. Compute P_{OS} which represents the maximum electrical demand for the outside sunlight period.
2. Equation 4 can be modified as equation 9:

$$B_{SPL} = \frac{P_{OS} \times D}{\eta} \tag{9}$$

Where

B_{SPL} is the battery storage for the priority loading concept

The value of P_{OS} is controlled by the home owners and can be limited to the following items:

- Television
- Lighting
- Refregirator
- Air-conditioning with limited energy consumptions. For example, for ducted air-condition with numerous outlets. the system can be operated on one outlet reducing the required electrical energy

III. SIMULATIONS

Figure 4 represents the proposed hourly energy consumption for the house under simulation. The major electrical equipment is:

- 2400W Air-conditioner
- 2200W swimming pool motor
- 1200W Vacuum cleaner
- 50W standard down light

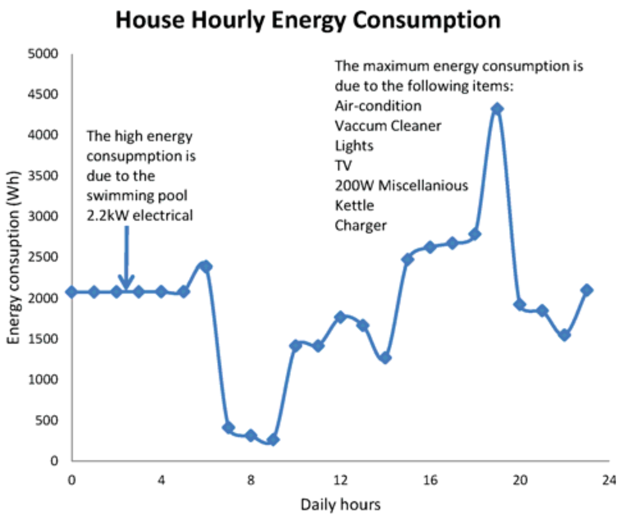

Figure 4. Hourly electrical energy consumption

The graph is based on the following assumptions:

- The swimming pool motor is set to operate overnight where the electric power is cheaper
- Air-condition on a hot day will operate at half power during the day and full power in the evening and early night time.
- The washing machine and drying will operate during the midday period
- Vacuum machine operates one hour in the morning and one hour at night

- During the night, only 6 of 50W lights are operated at the same time
- 200W worth of miscellaneous will be running for couple of hours during the night
- Cooking, heating and hot water is set for gas power
- The house maximum daily consumption is 45kWh. It is considered a large family home.

Applying the priority concept, figure 5 represents the updated hourly energy consumption of the same house. The figure is based on operating the following apparatus during midday period on a sunny day:

- Swimming pool electric motor
- Vacuum will be completed during the day
- The air-condition will operate at rated power during the day and half power in the evening and night
- Shift the miscellaneous power to midday
- Charge the equipment during the day

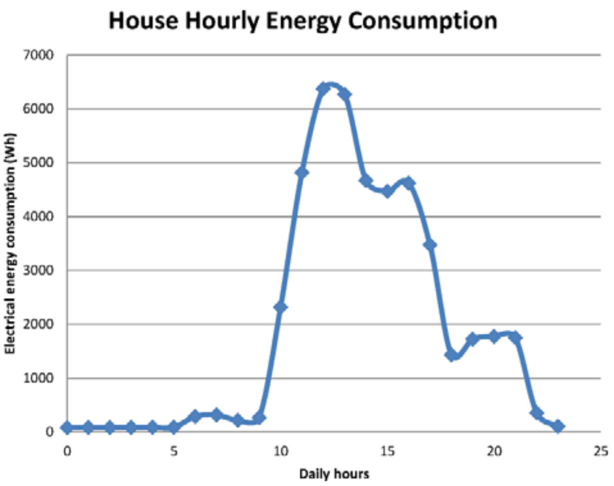

Figure 5. Updated hourly electrical energy consumption

IV. Discussion and Case Study

The simulation results show that it is possible to reduce the morning and night power consumption for a large house by shifting the power to midday period. The shifting of the energy offers the following benefits:

- Maximize the use of sun energy
- Reduce the electricity bill
- Reduce the maximum demand during peak hours
- Reduce the size of storage batteries required to support the house load overnight.

In addition to the above, the smart management system [7] automate these activities and provide the house owners with numerous options that lead to cost and energy saving.

A. *Case Study*

The case study is based on a two-story residential house with four bedrooms, kitchen, two living areas, two bathrooms and a swimming pool. The proposed household electrical apparatus is shown in table 2. The house daily consumption is 30.23kWh which is P_{MD}.

TABLE II. Proposed House Electrical Demand

Details of electric apparatus	Electrical Power (Wh)	Number of Operating hours/day	Proposed daily kWh
Refrigeration	45	24	1.1
Air-condition	1800	6	10.8
Washing Machine	350	1	0.35
Dryer	400	1	0.4
Toaster	1200	0.3	0.36
Kettle	700	1	0.7
Lights	240	6	1.44
Televisions	180	6	1.08
Vacuum Cleaner	2000	1	2.0
Chargers	200	2	0.4
Pool motors	1800	6	10.8
Miscellaneous	400	2	0.8

It is assumed that P_h is 3.6kW, therefore, $P_i = 5.6kW$

The case study follows the proposed diagram in figure 2 to determine the PV requirements. The battery storage is designed to hold the load for one day with a maximum discharge rate of 0.6. Therefore, equation 4 gives:

$$B_{Storage} = \frac{30.23 \times 1}{0.6} = 50.383kWh$$

It is assumed that 16 precents of the PV panels output is wasted, therefore, equation 5 gives:

$$E_{PV} = \frac{30.23kWh}{0.86} = 35.151kWh$$

The solar system has to provide a minimum of 35.151kWh per day. The worst case scenario is during winter, when the average sun-hours in winter is four hours. Therefore, the total number of PV panels required is 36. The house will use 250W panels with V_{oc} of 37V.

The charger controller that is chosen has the following characteristics:

- Maximum PV panels input power is 2kW
- Maximum PV input voltage is 150V
- Minimum PV input voltage is 40V
- Maximum charger current is 100A at 48V

Equation 6 is used to compute the number of panels in series:

$$N_{PV} = \begin{cases} \frac{150}{37} = 4.05 \\ 4 \times 37 > 40 \\ 4 \times 250 < 2000 \\ \end{cases}$$

The maximum number of panels connected in series is 4, therefore, nine arrays of 4 panels is required for the PV system design.

Based on the assessment, the design has the following requirements:

- 36 panels of 250W
- 50.383 kWh of battery storage
    - Using 48V 1050AH battery bank
- 2 charger controllers are required for the system
    - The system must have the ability to charge the battery within 4 hours
- 48V DC-AC inverter with instantaneous power of more than 5.6 kW

The cost of the batteries, as per the current market is too high (almost $1000 per kWh). This prevents the individual investment in a 100 percent sustainable system.

Applying the priority concept, the home owners require the following appliances to be operated outside sunlight hours:

- Television
- Lighting
- Refregirator
- Air-condition for summer period only (Heating for winder relies on gas or wood)

$$P_{OS} = (45 \times 20) + (240 \times 6) + (180 \times 6) + (1800 \times 6)$$
$$\Updownarrow$$
$$P_{OS} = 14.22 kWh$$

The energy storage requirement is computed using equation 9:

$$B_{SPL} = \frac{14.22 \times 1}{0.6} = 23.7 kWh$$

The updated battery storage represents 47 percent of the battery storage as per equation 4. This reduction reduces the cost of the system and makes it more attractive to homeowners.

It proves that homeowners play vital role in reducing the size of the battery storage. It illustrates the large saving in energy storage if the priority concept is followed. In addition, the number of panels for the case study can be reduced based on the following:

- The energy storage to supports the air-condition exceeds the 10kWh
- The energy storage for winter is around 4kWh
- The sun hours for summer is almost double than that of winter, refer to figure 3.
- Based on equation (8), the number of solar panels can be reduced when priority list is used

Therefore, the design system is a conservative system that supplies the household for one-day cycle.

V. CONCLUSION

The paper addresses the minimum design requirements for a PV solar system with battery storage. The case study supports the proposed priority concept that reduces the battery storage size. The proposed concept reduces the investment budget and makes the solar system more attractive to individuals.

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