Smart Design of Stand-Alone Solar PV System for Off Grid Electrification Projects

Parimita Mohanty and Tariq Muneer

Abstract Solar PV has seen a remarkable growth across the globe with the total PV installation now exceeding several gigawatts (GW). The technology has the versatility and flexibility for designing systems in different regions, especially in remote rural areas. While conventionally straightforward designs were used to set up off-grid PV-based systems in many areas for a wide range of applications, it is now possible to adopt a smart design approach for the off-grid stand-alone solar PV system. A range of off-grid system configurations are possible, from the more straightforward design to the relatively complex, depending upon power and energy requirements, electrical properties of the load, as well as on site specificity, and available energy resources. The overall goal of the off-gird system design should be such that it can give maximum efficiency, reliability and flexibility of the system at an affordable price. In this chapter, the three basic PV systems, i.e. stand-alone, grid connected- and hybrid-systems are briefly described. Assessment of energy requirement including load profiling, load distribution and load categorisation is provided in a lucid way. That is then matched with a section on solar resource availability. Furthermore, a systematic approach has then been presented regarding sizing and designing of the above systems. Guidelines for selection of PV components and system optimisation are provided. Owing to the natural variance of the solar resource there is a critical need for storage batteries to satisfy energy demand during nocturnal and overcast periods. Furthermore, under a highly variable cloud regime there is a frequent demand for charging and discharging of battery in a PV system. So, the type of battery used in a PV system is not the same as in an automobile application. Detailed guidelines for selection of battery are therefore also provided.

P. Mohanty (✉)
The Energy and Resources Institute (TERI), New Delhi, India
e-mail: parimita@teri.res.in

T. Muneer
School of Engineering and the Built Environment, Edinburgh Napier University, Edinburgh, Scotland
e-mail: T.Muneer@napier.ac.uk

S. C. Bhattacharyya and D. Palit (eds.), *Mini-Grids for Rural Electrification of Developing Countries*, Green Energy and Technology,
DOI: 10.1007/978-3-319-04816-1_4, © Springer International Publishing Switzerland 2014

1 Introduction

One of the primary concerns in designing a solar photovoltaic (PV) system is the determination of the optimum relationship between the PV array and the other Balance of System to supply a required unit of energy at a certain level of reliability. In order to get higher reliability of the PV system, where the weather pattern and load profile of a site can hardly be accurately predicted, the system is generally oversized, making it highly expensive. However, there are several smart approaches of designing the solar PV system, which would not only help improve the reliability of the system, but would also assist in improving the efficiency of the overall system.

This chapter is an introduction to such a smart design approach for the off-grid stand-alone solar PV system. A range of off-grid system configurations are possible, from the more straightforward design to the relatively complex, depending upon its power and energy requirements, electrical properties of the load as well as on the site specificity and available energy resources. However, the overall goal of the off-gird system design should be such that it can give maximum efficiency, reliability and flexibility of the system at an affordable price. The experiences clearly show that clean energy systems in rural and remote locations need to be designed, taking into account that access to frequent service, repair and maintenance is difficult, that is, the system performance should be reliable. Also, since the capital cost of clean energy systems is usually high, it is imperative that the efficiency of such systems is optimised so that cost per unit of electricity generated is minimised. Lastly, the system should have a significant level of flexibility such that both the grid (when it is eventually extended to an off-grid site) and other sources of energy can be coupled with the system as and when required. Therefore, the option to easily connect to the grid and earn revenue from sale of electricity must exist. The above requirement can be met not through huge investment in capital cost but mainly through proper planning, optimum design and reconfiguration of the system. The incremental cost involved here can be easily recovered through the kind of efficiency, reliability and flexibility such type of system gives in the long run. While considering the above mentioned points, the following sections cover the designing of stand-alone solar PV system used in off-grid electrification projects.

1.1 Types of Solar PV Systems

PV systems are broadly classified into three distinct types:

1. *Stand-alone systems* where the power is generated and consumed in the same place and which does not interact with the main grid. Normally the electricity consuming/utilising device is part of the system, i.e. solar home systems, solar street lighting system, solar lanterns, and solar power plants.

2. *Grid-connected systems* where the solar PV system is connected to the grid. The grid connected system can either be a grid tied system, which can only feed power into the grid and such system cannot deliver power locally during blackouts and emergencies because these systems have to be completely disconnected from the grid and have to be shut down as per national and international electrical safety standards for both safety reasons. On the contrary, grid-interactive PV systems with their bi-directional energy transfer capability can not only connect to the public utility grid but can also provide power locally in case of an islanding condition. In this way, grid interactive system provides commercial and other users highly reliable and cost-effective energy while staying environmentally aware and responsible.
3. *Solar PV-hybrid system* In a hybrid system another source of energy, such as wind, biomass or diesel, can be hybridised to the solar PV system to provide the required power. Here, the objective is to bring more reliability into the overall system at an affordable way by adding one or more energy source(s).

Although this chapter focuses more on design approaches adopted for stand-alone solar PV system, it also mentions how certain approaches in design and component selection should be taken care of from the beginning in order to upgrade the stand-alone system into a hybrid or grid interactive or grid tied system in future with minimum interventions and incremental cost involvement.

2 Guidelines for Smart Designing of Stand-Alone Solar PV Systems

A systematic approach is important and required when sizing and designing stand-alone solar PV systems. The following procedures are generally followed

A. Planning and site survey
B. Assessment of energy requirement and solar resource availability
C. Sizing of main component of the PV systems
D. Selection of main components of PV system.

2.1 Planning and Site Survey

The output of PV array is site specific. For the generation of maximum power, it is important to choose the best site for the array. The maximum power will be obtained if the module area is exposed to direct sunlight for a maximum period of a day. Therefore, the first thing that needs to be done in a PV system design is site survey and planning in order to avoid site-related confusion and contradiction at a later stage. The following points need to be covered during the site survey to check the suitability of the site [1]

- site orientation, total land area/surface area of roof available;
- structure and type of roof;
- possible routes for cables, battery and inverter location;

The proposed site for installation can be surveyed with a solar path-finder to check whether there is any possibility of seasonal shading problem. In addition to this, the most essential input parameters like incident solar radiation, the ambient temperature, and wind velocity, which are likely to vary widely from site to site, need to be collected for the specific site. The air temperature significantly affects the cell operating temperature (COT) and hence the output energy. So it is necessary to have access to the data and information on all these parameters in order to carry out an optimum PV system design exercise.

2.2 Assessment of Energy Requirement and Solar Resource Availability

In a stand-alone solar PV system, estimating the energy requirement and assessing the realistic solar resource availability are the most important tasks, which have to be done properly. This is also critical from the point of view of adding any smart load management and resource management features (see Box-1).

Following steps are adopted for carrying out this exercise

Box-1 Guidelines for system optimization

Efficient design lowers the initial system expenses. For example: reducing the electric lighting load by 75 % by shifting from incandescent to fluorescent lights or by reducing the load by 40 % by shifting from CFL to LED will reduce the modules and batteries needed for load. Eliminating module shading by relocating the mounting system does not cost any additional money and can increase the system's efficiency by a large percentage. Inefficiency caused by excessive voltage drop in the system's wiring can also be inexpensively eliminated. Intelligent advance planning doesn't have high incremental cost, but can drastically reduce system's initial cost.

In general the designer should consider some important points while trying to optimise the system [4]

- Siting a system correctly so that it is not shaded;
- Orientation of the system is a critical element in maximising annual PV output based on local climatic conditions;
- Mounting options can maximise or even increase insolation gain;
- Modules should be selected according to a system's parameter;

- Wiring should be designed to minimise voltage drop;
- Controllers must operate a system efficiently while meeting the needs of the system;
- Battery storage must be sized to the specific installation (For how long the system should work when the sun is not shining).
- Loads determine the size of the system and should be minimised by intelligent planning.

2.2.1 Load Profiling, Load Distribution and Load Categorisation

The load of a particular site may vary from season to season and event to event. Sometimes, the load may be as low as few watts (W) and sometimes it may be as high as few kilowatt (kW). Therefore, it is important to assess the type and utilization of such load and profiling of that load. The first step is to identify and enumerate the typical load, which can vary from simple lighting load to heavy motor load, and its characteristics as per Table 1. The power rating of the appliances can be obtained from catalogued information. If details are not provided, the power rating can be assumed to be the same as other similar appliances.

Once the type of the load is identified, the next step is to map the distribution of these loads and create the load distribution map; this is critical from design point of view as it helps in estimating the number of feeders to be used, routing of the distribution feeders, length of the distribution cable/feeder and sub-feeder, voltage drops, total power losses in cables, etc. It will also help in identifying the actual location of the street lights and the solar PV power plant to be installed. Typical load distribution maps from site (as shown in Fig. 1) can be created.

Once the load distribution is made, load at different feeder as well as the total load is calculated and the information is filled as per Table 2.

A graph between time of the day (*X*-axis) and total load at solar PV power plant end (*Y*-Axis), i.e. load profile can be plotted as shown in Fig. 2.

Box-2 Calculate load and energy-related requirement Calculate

- Total connected Watts
- Average daily daytime energy requirement
- Average daily nocturnal energy requirement.

Table 1 Load details

Load appliances	Number of household (No.)	AC or DC load	Number of load (No.)	Power rating of each load (W)	Single phase (1Φ) or three phase (3Φ)	Total power required (W)
Lights						
Fans						
Street lighting						
Water pump						
Others						
Load 1						
Load 2						
Load 3						
Total						

Source This study

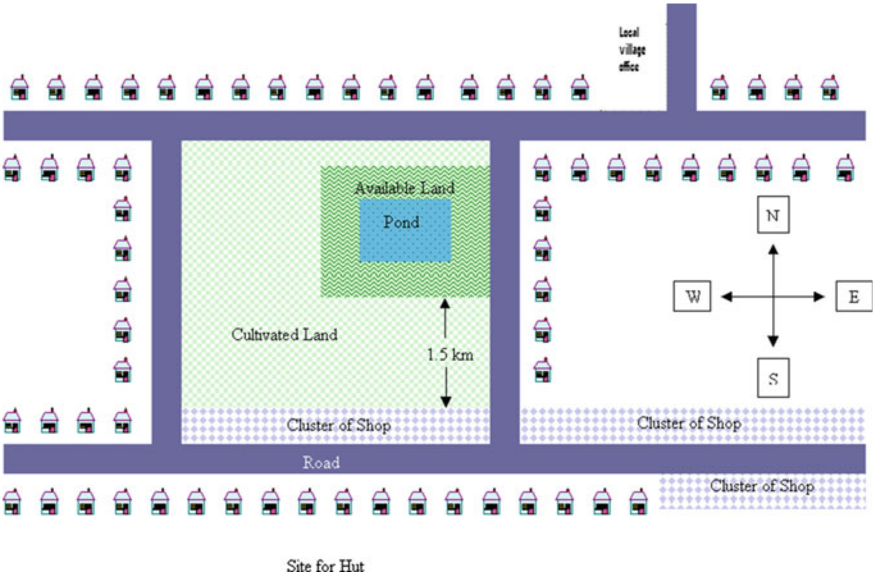

Fig. 1 Typical load distribution maps (*Source* Authors' compilation)

Based on the load profile, the total connected load (Watt ac) and "Average daily daytime energy requirement" (Watt-hour) and "average daily nighttime energy requirement" (Wh) may be calculated as indicated in Box-2.

Subsequently the load can be categorised based on their priority and load profile. There are 2–3 ways of categorising the load and each of the load categorisation is done in order to meet certain objectives. Table 3 shows the type of load and its category

Table 2 Load at different feeder

Time (Hrs)	Load at feeder 1(W)	Load at feeder 2 (W)	------	Load at feeder n (W)	Total load at solar PV power plant end (W)

Source: this study.

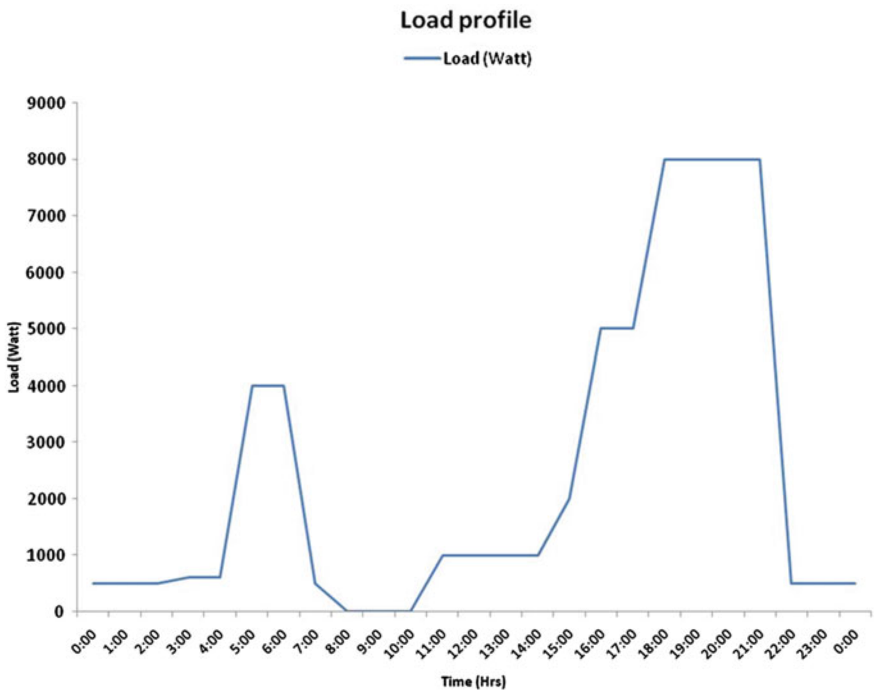

Fig. 2 Load profile of the proposed site (*Source* Authors' compilation)

- In order to design the configuration and optimum capacity of the energy storage system as well as the entire mini-grid system optimally and efficiently, the total load of each of the site is categorised into (i) day load and (ii) night load.

Table 3 Type and category of load

Category of load	Type of load
Daytime load	
Nocturnal load	
Critical load/Essential load	
Non-essential load	

Source Author's compilation

- Furthermore, in order to give preference to certain loads over others in case of limited availability of energy (for which only certain loads can be chosen to which energy can be supplied), the loads are also categorised based on their priorities, i.e. critical or essential load and (ii) non-essential load.
- From the tariff payment point of view, the loads can also be categorised as (i) minimum load, and (ii) desirable load based on the willingness to pay.

The advantage of categorising the load during the design stage is that it will allow automatic connects/disconnects of certain loads based on their priorities. For example, let us assume that there are certain non-essential loads, which are not as critical as the lighting load of the household. In that case, if adequate power is not available from the solar system and the battery is not amply charged, then the non-essential loads can be disconnected automatically, without affecting the smooth operation of the critical or priority load.

2.2.2 Assessment of Solar Energy Resource

The assessment of solar energy resource is very important from the sizing point of view because that helps in estimating the output of the solar module or array and also assist in identifying the appropriate PV technology to be used for the PV power system. Hence, in this exercise, solar radiation falling on the plane of the solar array is to be assessed. Solar radiation consists of direct radiation and diffuse radiation and the value for both of those components should be known. The total of direct and diffuse radiation is known as the global solar radiation.

Solar radiation is measured in units of solar energy falling on a horizontal surface over a period of time—the standard unit is kilowatt-hour per square metre (kWh/m^2). This is usually available for an average year or for an average day in a given month.

While assessing the solar energy resource, the following information is to be collected [4]

- Average annual global solar radiation and average daily global solar radiation (kWh/m^2) on horizontal surface;
- Monthly-averaged daily global and diffuse solar radiation on horizontal surface (as shown in Fig. 3);
- How many sunny days and overcast days occur in a year;

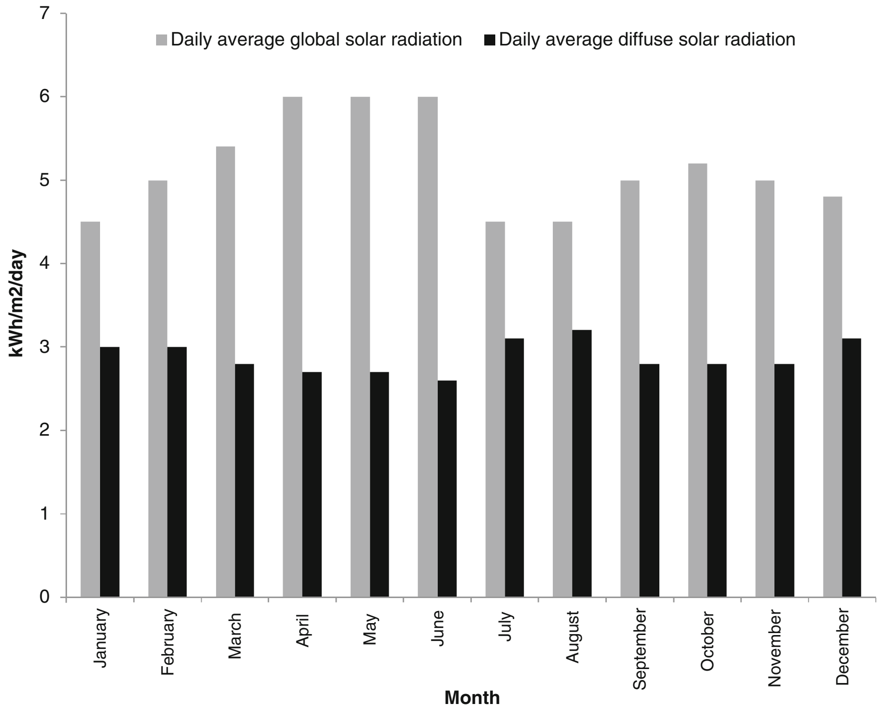

Fig. 3 Monthly-averaged daily global direct and diffused solar radiation on a horizontal surface

The above monthly-averaged data can be obtained from NASA surface meteorology website or similar authorised national solar energy resource centres. However, since the power output of the solar array depends upon the incident solar radiation, the solar radiation falling on the horizontal surface needs to be adjusted with a *modification factor* (*which is generally in the range of* 1.03–1.1) in order to take the surface tilt and orientation into consideration. This information is used in the subsequent section for estimating the sizing of the solar PV array.

2.2.3 Sizing of Main Component of the PV System

One point that needs to be decided at this stage is the *System Voltage*, i.e. whether a 12, 24, 48 V or higher voltage is chosen. This is critical from the point of view of determining the capacity of the components. Once the system voltage is chosen, the following steps can be followed for sizing the power system.

Step I: Specifying the inverter rating

i. Calculate "total connected AC Wattage";
ii. Capacity or rating of the inverter should be the nearest higher value to the "total connected AC Watt";

iii. Define the efficiency of the inverter (η_{inv})—This value can be taken from the technical brochure or specification chart of any of the reputed inverter manufactures;

Capacity or rating of inverter $\geq$ total connected AC Wattage

More details on how to select the inverter are provided in Sect. 5.

Step II: Specifying the battery capacity

The capacity of the battery depends upon three things: (a) daily energy requirement (E, W h); (b) days of autonomy (A) (i.e. number of days for which storage is required) and (c) maximum allowable Depth of Discharge (DoD) of the battery.

This approach for determining the capacity of the battery is different in a smart design concept than from a standard design approach. In a standard design, the capacity of the battery is decided based on the total daily energy requirement E. It does not segregate between the daytime energy requirement and night-time energy requirement. The difference between these design approaches does not seem substantial if there is no or little daytime load and daytime energy requirement. But it makes considerable difference if there is considerable daytime energy requirement.

For a daytime load, there is no need of storing a large proportion of solar generated DC electricity in battery. Rather, the DC electricity can be directly converted to AC electricity through the inverter. This would result not only improve the efficiency of the entire system (by around 5–7 %), but would also lead to smaller capacity of the battery and thus reduce the capital as well as replacement cost of the battery. However, the battery capacity should be such designed, that it can take care of the sudden fluctuation in the solar radiation (such as swift movement of clouds would result in a sudden drop of solar irradiation). So, in order to cater to the above points, on an average, 5–8 % of the daytime energy requirement can be added to the nocturnal energy requirement to find out the ideal *daily energy requirement,* which is used to design the battery capacity.

Daily energy requirement (for battery sizing) E = nocturnal energy requirement + 0.08 $\times$ day-time energy requirement

Secondly, to find out the days of autonomy, we need to take a decision on the following:

(a) whether to increase the capacity of the solar PV array in such a way that there would not be any situation when load requirement is more than the generated solar electricity and thus there is no extra day for storing energy in battery

or

(b) certain number of extra days (generally 2–3 days) is considered for storing energy in battery

or

The value of global solar radiation at horizontal surface (kWh) is equivalent to the peak sun-shine hours or Equivalent Hours of Sunshine (EHSS). The relationship is as follows

kWh = Peak power of the module (Wp) × Number of peak sunshine hours *Number of peak sunshine hours* is the total number of hours when the module is exposed to the standard test condition of 1,000 W/m^2, 25 °C and AM of 1.5.

(c) solar PV array is sized in such a way that it can cater to the required energy in most of the months in a year and in the remaining month battery can be charged through another energy resource (such as diesel or wind generator) and thus there is no extra day (or maximum one day) for storing energy in battery.

From the smart design point of view, option (a) and (b) will not be recommended as it will permit an unnecessary increase in the designed size of solar PV array or battery. Instead, option (c) can be considered.

Box-3

In a *standard design* the battery capacity is done based on the total daily energy requirement, whereas in *a smart design concept* the battery sizing is done based on the total nocturnal energy requirement and 5–8 % of the daytime energy requirement.

Once the above-mentioned information is collected, the minimum capacity of the battery, Q required in Ampere-hour (Ah) can be calculated as per the formula given in Eq. 1 [1]

$$\boxed{Q = \frac{(E \times A)}{V \times T \times \eta_{\text{inv}} \times \eta_{\text{cable}}}} \tag{1}$$

where,

E	Daily energy requirement for battery sizing (Wh)
A	Days of autonomy, i.e. number of days of storage required
V	System voltage
T	Maximum allowable depth of discharge of the battery (0.3–0.9)
η_{inv}	Inverter efficiency (0.8–0.95)
η_{cable}	efficiency of the cables delivering the power from the battery to the load.

The maximum allowable depth of discharge of the battery depends upon the type as well as characteristic of the battery (*whether lead acid battery—flooded type*, *Sealed Maintenance Free* (*SMF*), *Valve Regulated Lead Acid* (*VRLA*) *or gel type*; *lithium* (Li) *based—lithium ion*, *lithium phosphate*, etc.). More details about the selection of the batteries are given in Sect. 4.

Step III: Sizing of solar PV array

In a standard design, the sizing of the solar PV array in a stand-alone solar PV system can be done by using the Eq. 2

$$\boxed{W_{PV} = E_{total} \div \text{ESSH} \div \eta_{sys,\,overall}} \tag{2}$$

where,

W_{PV}	Peak wattage of the solar PV array
E_{Total}	Total daily energy requirement in Watt-hour (Wh)
ESSH	Equivalent Hours of Sunshine (i.e. Peak Sunshine hours)
$\eta_{sys,overall}$	Total system efficiency which includes the losses on account of PV array mismatch, cable losses, losses within inverter and charge controller, battery Ah-efficiency, etc. Here the value is around 0.6.

In general, overall efficiency is calculated as given in Eq. 3

$$\eta_{sys,\,overall} = \eta_{PV} \times \eta_{cable(PV,\,bat)} \times \eta_{cc} \times \eta_{batt} \times \eta_{inv} \times \eta_{distb\ cable} \tag{3}$$

where,

$\eta_{sys,overall}$	Total system efficiency
η_{PV}	Losses due to array mismatch, dirt, shading, etc. the efficiency ~90 %
$\eta_{cable\ (PV,bat)}$	Losses due to voltage drops in cable from PV array to battery (value ~98 %)
η_{cc}	Charge controller efficiency (value ~98 %)
η_{inv}	inverter efficiency (value ~90 %)
η_{batt}	Battery Ah efficiency (value ~85 %)
$\eta_{distb\ cable}$	losses in distribution cables (value = 98 %).

In a smart design, the sizing of the solar PV array can be achieved by estimating and adding the following

a. Solar PV array sizing for supplying the daily energy required for the battery; and
b. Solar PV array sizing based on daily daytime energy required.

Solar PV array capacity for supplying the daily energy required for the battery can be obtained as per the formula given below (Eq. 4),

Table 4 Total capacity of PV array required with different combination of energy requirement

Total energy required (Wh)	Daytime energy required (Wh)	Night time energy required (Wh)	Total size of PV array required (Wp)
4,000	0	4,000	1,350
4,000	1,000	3,000	1,250
4,000	2,000	2,000	1,170
4,000	3,000	1,000	1,090
4,000	4,000	0	1,000

Source This study
Note ESSH of 5 h is considered

$$\boxed{W_{PV-batt} = E \div \mathrm{ESSH} \div \eta_{sys,overall}} \tag{4}$$

where,

$W_{\text{PV-batt}}$ Peak wattage of the array
E Total daily energy requirement for battery in Watt-hour (Wh)
ESSH Equivalent Hours of Sunshine (i.e. Peak Sunshine hours)
$\eta_{sys,overall}$ Total system efficiency (~65 %) which includes the losses on account of PV array mismatch, cable losses, losses due to inverter and charge controller, battery Ah-efficiency etc.

Solar PV array capacity for supplying the daily daytime energy required can be obtained as per Eq. 5

$$\boxed{W_{PV-daytime} = E_{day} \div ESSH \div \eta_{sys,\,daytime}} \tag{5}$$

where,

$W_{\text{PV-batt,daytime}}$ Peak wattage of the array
E_{day} Total daily daytime energy requirement in Watt-hour (Wh)
ESSH Equivalent Hours of Sunshine (i.e. Peak Sunshine hours)
$\eta_{sys,daytime}$ System efficiency which includes the losses on account of PV array mismatch, cable losses, losses due to inverter and charge controller (value is around 80 %).

The total solar PV capacity requirement can be calculated by adding $W_{\text{PV-batt}}$ (Eq. 4) and $W_{\text{PV-daytime}}$ (Eq. 5)

$$\boxed{W_{PV} = W_{PV-daytime} + W_{PV-batt}.} \tag{6}$$

The table below (Table 4) shows how the total capacity of the PV array varies with different combination of daytime energy requirement and night-time energy requirement although the total energy requirement is kept fixed.

As per Table 4, in case of standard design, the total capacity of the PV array required for meeting the daily energy requirement of 4,000 Wh is 1,350 Wp irrespective of whether it is used in daytime or night-time. However, if smart design concept is followed, total capacity of the solar PV array can be reduced based on their daytime and night-time energy requirement.

Caution

Although system design is made based on certain assumptions, it is difficult to predict how a system will be used in practice, particularly in an off-grid location. Therefore, it is also difficult to predict the realistic energy requirement. Again there is every possibility that although the loads are designed for daytime but it might be used in night-time or vice versa. Therefore, in a smart design concept, these uncertainties are also addressed by having additional protections for the load sensitive components, specifically for the batteries. Here, in a worst case scenario, if energy withdrawn from the battery bank is very high compared to the available energy, then some of the loads, which are not very critical (*non-essential load*), are automatically disconnected depending upon the State of Charge of the battery.

Step IV: Sizing system wiring

The following steps can be followed to size the system wiring [4]

i. Divide the "AC total connected Watts" by the "DC system voltage". This will provide "Maximum DC amps continuous" which the system will have to provide;
ii. The above value will be used to size the cable from battery to inverter. That is the "maximum array amps" the controller would encounter under a short circuit condition.

Power losses and voltage drop in a PV system

Assessing the power loss and voltage drop is very critical in a PV system particularly if it is a small power system of few kW and the power is distributed to a large distance. If it is not assessed properly and realistically, this may lead to severe problems in the system, such as

- Battery might not get charged properly due to large voltage drop in the cable between the solar module and the battery;
- Some appliances may not work properly or get damaged if the voltage reaching them is quite low as compared to its operating voltage level.

So here, the voltage drop at each section (solar *array to battery*, *battery to inverter*, *inverter to load distribution box*, *in the local distribution network*, etc.) of the PV system should be calculated.

Voltage drop within the PV system can be calculated as follows

$$V_D = 1 \times R_c$$

where,

V_D the voltage drop in the cable
I the current in the cable and
R_c the cable resistance, which depends upon cable length and cross sectional area.

Generally, the cable length and the cross sectional area is chosen in a such a way that voltage drop between any two sections of the PV system is within the permissible voltage level. Most national electric code provides a method to calculate the voltage drop and cable size for the range of cables approved in the code either through the formula or by using the guidance tables. The designer or installer should make them familiar with the guidance table and the concerned formula in order to identify the appropriate cable size and type for a defined distance. The load distribution map developed during the initial stages of the design would be used here to carry out the power loss/voltage drop assessment exercise.

3 Guidelines for the Selection of PV Components

The following sections discuss the critical points that are to be considered while selecting the critical components of the PV system such as PV modules, batteries, inverter and charge controller.

3.1 Guidelines for Selection of PV Module

In principle, while procuring a module or an array, the following parameters have to be considered.

- PV module electrical characteristics and its specification;
- PV module temperature tolerance, hail impact resistance;
- PV module efficiency, dimension and weights;
- PV module with system compatibility;
- PV Quality requirement, Quality marks, standard and specifications; and
- PV module warranties and guarantees.

3.1.1 PV Module Electrical Characteristics

The PV module electrical characteristics cover

- Open circuit voltage (V_{oc});
- Short circuit current (I_{sc});
- Voltage at the maximum power point (V_m);
- Current at the maximum power point (I_m);
- Peak power (P_m); and
- Fill Factor (FF).

For a solar power plant, modules with higher wattage should be used because it will require less number of modules thus covering less roof area, fewer mounting structure, fewer inter-module electrical connections, etc. Power tolerances are also very critical and these need to be checked before the purchase of the module as the module output varies significantly on the negative side and can badly reduce the total output of the array due to array mismatching. Generally power tolerance of PV module is ±3 to ±5 %.

3.1.2 PV Module Temperature Tolerance, Hail Impact Resistance

The open circuit voltage of an individual silicon solar cell reduces by 2.3 mV per degree rise of cell temperature. Therefore, the temperature coefficient of the voltage is negative and expressed as shown in Eq. 7

$$ {}^{\mathrm{d}V_{oc}}/_{\mathrm{d}T} = -2.3\,\mathrm{mV}/^{\circ}\mathrm{C}. \tag{7} $$

As a module consists of large number of cells in series, the voltage coefficient is very large, which is expressed as shown in Eq. 8

$$ {}^{\mathrm{d}V_{oc}}/_{\mathrm{d}T} = -2.3 n_c\,\mathrm{mV}/^{\circ}\mathrm{C} \tag{8} $$

where n_c is the number of cells in series.

The temperature coefficient of the current is slightly higher and the current increases very slightly with increase in cell temperature. However, the temperature coefficient of the power is negative for the silicon solar cell, whereas that of the thin film it is positive. That means, with the rise in temperature, the power output of the thin film solar cell increases slightly as compared to decrease in power output for silicon solar cell. This temperature coefficient effect needs to be taken care of in the system design and in estimating the yield of a PV array.

3.1.3 PV Module Efficiency, Dimension and Weight

PV module efficiency has a practical relevance because module with lower efficiency will simply cover a larger roof space (to provide the same power output), which is not a problem if there is a considerable surface area available. So, if the per Wp cost of the solar module is substantially lower for the lower efficiency module, then it makes sense to install relatively lower efficiency modules. So, here module with same Wp but of different efficiencies can be compared with their cost and the available area. The most optimum module can thus be chosen.

3.1.4 PV Module with System Compatibility

PV module or array should be compatible with the rest of the electrical components in the system. Particularly, the PV module or array's electrical characteristics should be compatible with the inverter, charge controller and the batteries. For example, the voltage of the PV string should match with the battery voltage in order to charge the battery appropriately or it should match with the input voltage required for the inverter in order to provide the desired AC output.

3.1.5 PV Quality Requirement, Quality Marks, Standard and Specifications

Modules which comply with appropriate national and international standards developed by recognised institutions, such as International Electrotechnical Commission (IEC), American Society for Testing and Material (ASTM), Sandia National Laboratory, etc. can be considered as reliable and likely to have longer life. The compliance of the standard will also take care of the minimum degradation of power output (%) from solar PV module in a defined time period.

3.1.6 PV Module Warranties

PV module warranties are extremely critical and the modules where the output will be guaranteed to be a minimum of 80 % of its original rating after 20–25 years should be purchased.

3.2 Performance Comparison of Different PV Technologies

Based on the site-specific conditions and requirements, Table 5 helps in identifying the most appropriate PV technology that is to be used.

Table 5 Performance of different PV technologies

	Mono-crystalline	Poly-crystalline	Thin-film		
			Amorphous	Cadmium Telluride (CdTe)	Copper Indium Gallium di-selenide (CIGS)
Typical module efficiency	15–20 %	13–16 %	6–8 %	9–11 %	10–12 %
Best research cell efficiency	25.0 %	20.4 %	13.4 %	18.7 %	20.4 %
Area required for 1 kWp (in m^2)	6–9	8–9	13–20	11–13	9–11
Typical length of warranty	25 years	25 years	10–25 years		
Temperature resistance	Performance drops 10–15 % at high temperatures	Less temperature resistant than mono-crystalline	Tolerates extreme heat	Relatively low impact on performance	
Additional details	Oldest cell technology and most widely used	Less silicon waste in the production process	Tend to degrade faster than crystalline-based solar panels		
I–V curve fill factor (idealised PV cell is 100 %)	73–82 %		60–68 %		
Module construction	With anodized aluminium		Frameless, sandwiched between glass; lower cost, lower weight		
Inverter compatibility and sizing	Lower temperature coefficient is beneficial		System designer has to consider factor such as temperature coefficients, $V_{oc} - V_{mp}$ difference, isolation resistance due to external factors		
Mounting systems	Industry standard		Special clips and structures may be needed. In some cases labour cost is significantly saved		

NB Authors' compilation, 2014

Table 6 Comparisons of two cases of solar PV system

Details	Solar system 1	Solar system 2
Manufacturer	A	B
Model	M1	M2
Efficiency	17 %	16 %
Number of solar panels	40	40
Output (year one)	8,000 kWh	9,000 kWh
Total cost	$40,000	$36,000
Area	34.8 m^2	45.1 m^2
Value	$5/kWh	$4/kWh

Let us now apply the above guidelines for selection of PV system assuming the following cases provided in Table 6. From a financial point of view, solar PV system 2 makes more sense for the consumer to buy and install. However, solar PV system 1 may make more sense if space for system installation is a constraint.

4 Guidelines for the Selection of Battery

Since solar modules can generate power only when exposed to sunlight, there is a need for storage batteries to store energy collected during periods of high irradiance and make it available at night and also during overcast period. There is a frequent demand for charging and discharging of batteries in a PV system. So, the type of battery used here is not the same as an automobile battery. Figure 4 shows the different categories of batteries.

The following types of batteries are available for PV application

- Lead acid battery (most common)
- NiCd (Nickel Cadmium)
- NiMH (Nickel Magnesium Hydroxide)
- Lithium based

Lead acid batteries are most widely used in solar PV application. Currently, lithium ion-based batteries are also being used in solar PV applications, particularly for small scale applications. While the useful life of the battery increases, the installation cost becomes very high in such cases. Other battery types, such as NiCd or NiMH, are used in portable devices. Typical solar system batteries' lifetime spans from 3 to 5 years. We can, however, achieve life of around 6–8 years with proper battery management and regular preventive maintenance of the battery bank. There are a large numbers of batteries available in the market and each of these is designed for a specific application.

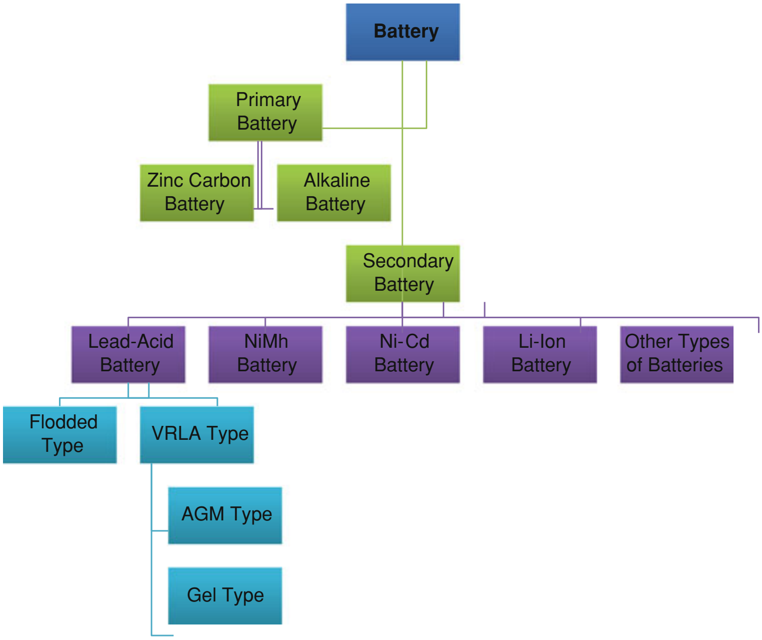

Fig. 4 Categorization of batteries (*Source* Author's compilation)

For product designers, an understanding of the factors affecting the battery capacity and life is vitally important for managing both product performance and warranty particularly with high cost batteries. Following characteristics are very important while selecting a battery used for solar application.

- Battery capacity at what rate
- Cycle life and temperature
- Battery Ah efficiency
- High charging current capability
- Good reliability under cyclic, deep discharge conditions
- Good power density, high recharge efficiency, rapid rechargeability
- Maintenance free, wide operating temperature
- Low cost per Ah, low self-discharge rate.

4.1 Battery Capacity

The capacity of a battery is measured in Ampere-hour (Ah). It provides information on the number of hours a specific current can be delivered by a fully charged battery before it gets completely discharged.

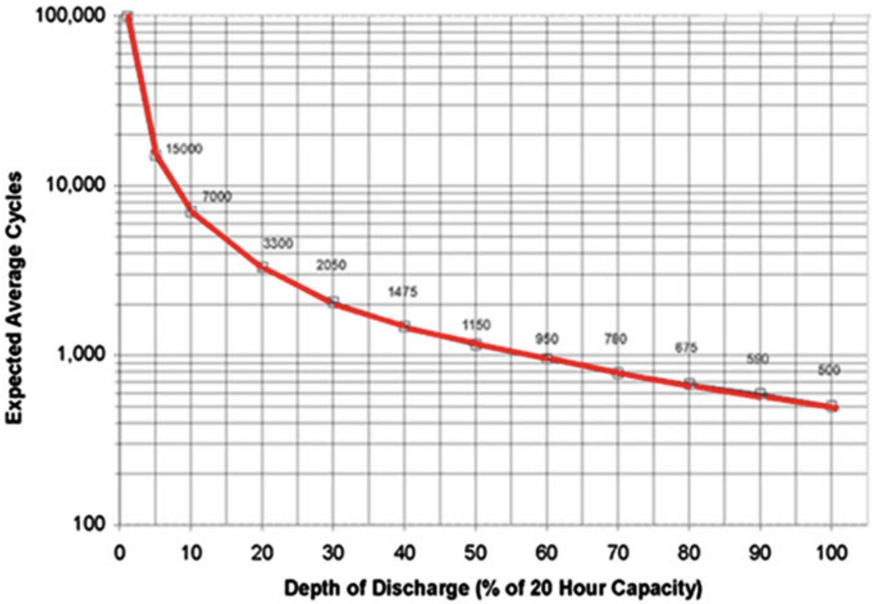

Fig. 5 Depth of discharge versus cycles of battery discharge (*Source* Author's compilation)

Battery capacity depends on

- *Discharging current*—the higher the discharging current the lower the capacity, and vice versa. For example: a battery delivering 1 A current for 100 h has a capacity of 100 Ah. However, if the same battery is discharged (delivering a current) with 8 A current it may provide that current for 10 h. That means the capacity is no more 100 Ah and instead reduces to 80 Ah (see Fig. 5). *Therefore, from the designer's perspective, the selection of the battery based on its capacity is important but more importantly at what rate* (*C*/10 *or C*/20 *or C*/100) *is most critical* [3]. *Because that decides what would be the actual capacity of the battery if it is not discharged at the designed rate.*
- *Temperature*. The capacity of the battery available in the market is specified at 25–27 °C. When the temperature exceeds, the capacity of the battery increases with temperature, whereas the life of the battery decreases (see Fig. 6). The performance of all batteries drops drastically at low temperatures. At −20 °C (−4 °F), most nickel-, lead- and lithium-based batteries stop functioning. Specially-built lithium ion brings the operating temperature down to −40 °C, but only on a reduced discharge. So, for lower temperature lithium ion battery can be chosen.

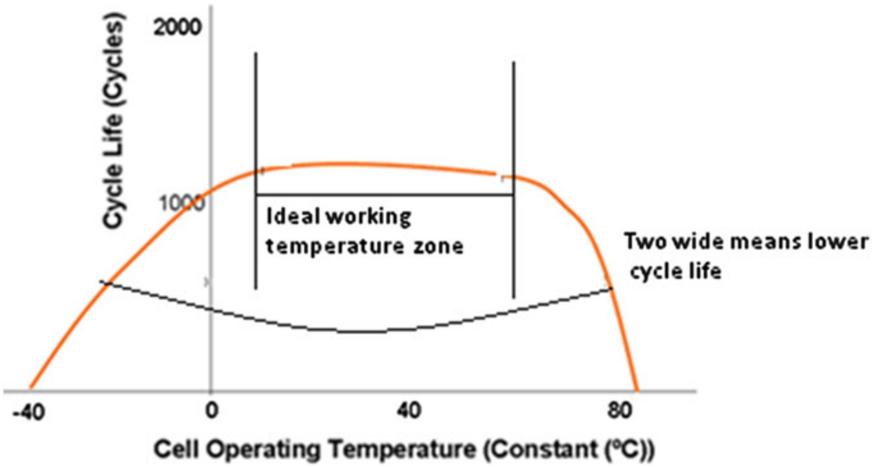

Fig. 6 Operating temperature of the battery versus cycle life

Figure 6 shows the ideal working temperature of the battery in order to get the optimum life cycle. Operating above 55 °C damages the battery permanently. One of the main functions of the battery management system is to keep the cells operating within their designed operating temperature window.

4.2 Life of a Battery

The life of the lead acid batteries is quoted as 5, 10, and 20 years. However this is a conditional statement and generally that condition is overlooked. The condition is the life of the battery will be *X* years, if the battery is kept in a specific temperature band, is kept at a specific float voltage. If these guidelines are not followed, the life of the battery will reduce. The rate of reduction of life depends upon how far its operation deviates from the designed value.

To supply a given load of *X* Watt, a bigger battery will be drained by a lower percentage, and would last for more cycles. That is to supply a 50 Ah load, a 100 Ah battery would be drained 50 %, whereas a 200 Ah battery would only be drained 25 %. The bigger battery will last longer. From Fig. 7, it can be seen that if the DoD changes from 50 to 25 %, then the life cycle of the battery would be more than doubled. Thus, a bigger battery is always recommended. But a bigger battery would also increase the cost. Thus, a balance between the cost of the battery and its capacity can be made to select the most appropriate capacity and type of battery.

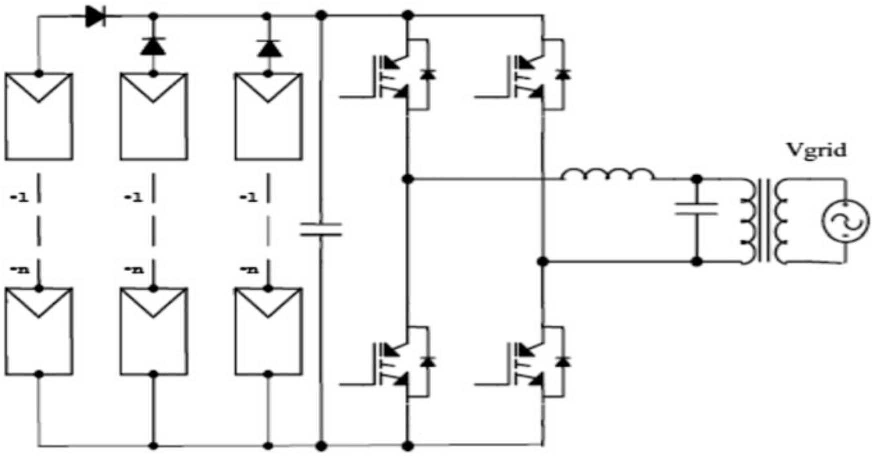

Fig. 7 Connections of solar PV strings

4.3 Self Discharge of Battery

This parameter is typically critical for a remote electrification project where the transportation of the material takes more time than standard time [1]. The typical self-discharge rates for common rechargeable cells are as follows:

- Lead Acid 4–6 % per month
- Nickel Cadmium 15–20 % per month
- Nickel Metal Hydride 30 % per month
- Lithium 2–3 % per month.

4.4 Comparison of Batteries Available in the Market

Table 7 compares the characteristics of four commonly used rechargeable battery used for solar applications, showing average performance ratings at the time of publication.

Based on the above-mentioned parameters, the appropriate battery for particular applications can be selected.

Table 7 Comparison of characteristics of different batteries

Specification	Lead acid	NiCd	NiMH	Lithium based		
				Cobalt	Manganese	Phosphate
Specific energy density (Wh/kg)	30–50	45–80	60–80	150–190	100–135	90–120
Cycle life	200–300	1,000	300–500	500–1,000	500–1,000	1,000–2,000
Fast charge	8–16 h	1 h	2–4 h	2–4 h	1 h or less	1 h or less
Overcharge tolerance	High	Moderate	Low	Cannot tolerate		
Self-discharge (month) from start	5 %	20 %	30 %	<10 %		
Maintenance requirement	3–6 months (topping)	30–60 days deep discharge	60–90 days deep discharge	Not required		
Cell voltage	2 V	1.2 V	1.2 V	3.6 V	3.6 V	3.3 V
Charge temperature	−20 to 50 °C	0–45 °C				
Charge temperature	−20 to 50 °C	−20 to 60 °C				
Safety requirement	Thermally stable	Thermal protection mandatory				

5 Guidelines for the Selection of Inverter

The size and capacity of the distributed solar PV system varies widely from few kW to MW scale and thus it is important to know whether selection on the type of inverters is different for different capacity of the PV system. The section below describes the different configurations that exist and its significance for PV system.

5.1 Single Stage/Central Inverter

The single stage inverter (central inverter) is widely used for large scale power applications. Here, the single power processing stage takes care of all the tasks of Maximum Power Point Tracking (MPPT), voltage amplification and grid side current control. In this configuration, the solar modules are connected in series to create strings with output voltage high enough to avoid an additional voltage boost stage [7]. In order to obtain the desired power level, the strings are connected in parallel through interconnection diodes (string diodes) as shown in Fig. 7.

Although this configuration is widely used, the global efficiency of the generation system is effectively reduced. The main reason of reduced performance is due to the centralised MPPT control that fixes a common operating point for all PV modules (shaded as well as un-shaded), whereas different operating points should be adopted for each module in order to extract the maximum power from the source. Because of these limitations, more advanced inverter topology is used based on the use of PV fields arranged in strings rather than arrays.

5.2 Double or Multi-stage Inverter

Here each string is connected to a double- or a single-stage inverter. If a large number of modules are connected in series to obtain an open circuit voltage higher than 360 V, the DC/DC converter can be eliminated. On the other hand, if a few number of PV modules are connected in series; a DC/DC boost converter is used. The DC–DC converter is responsible for the MPPT and the DC–AC inverter controls the grid current.

5.3 Multi-string Multi-stage Inverters with High Frequency Transformer

Another topology adopted is multi-string multi stage inverter. The multi string inverter has been developed to combine the advantage of higher energy yield of a string inverter with the lower costs of a central inverter. Lower power DC/DC converters are connected to individual PV strings. Each PV string has its own MPPT, which independently optimises the energy output from each PV string. All DC/DC converters are connected via a DC bus through a central inverter to the grid. Depending on the size of the string the input voltage ranges between 125 and 750 V. Here, system efficiency is higher due to the application of MPPT control on each string and higher flexibility comes from the ease of extensions for the photovoltaic field. This topology is more convenient for power levels below 10 kW. The multi-string inverters provide a very wide input voltage range (due to the additional DC/DC-stage), which gives the user better freedom in the design of the PV-system. However, the disadvantages are that it requires two power conversion stages to allow individual tracking at the inputs.

5.4 Selection of Inverter Based on Switching Devices

To effectively perform Pulse Width Modulation (PWM) control for the inverter, Insulated Gate Bipolar Transistor (IGBT) and Metal Oxide Semiconductor Field Effect Transistor (MOSFET) are mainly used for switching devices. *IGBT is used in more than* 70 % *of the surveyed inverter products and MOSFET is used in around remaining* 30 % *of the inverter*. As far as differences in characteristics between IGBT and MOSFET are concerned, the switching frequency of IGBT is around 20 kHz and it can be used for large power capacity inverters of exceeding 100 kW [6]. On the other hand, although the switching frequency of MOSFET can go up to 800 kHz, its power capacity is reduced at higher frequencies and MOSFET are used for output power range between 1 and 10 kW. So, in a nutshell, both IGBT and MOSFETs are used for small to medium range PV system with power capacity of 1–10 kW, whereas IGBTs are used for large scale power plant with power rating equal to or more than 100 kW. High frequency switching can reduce harmonics in output current, size, and weight of an inverter and thus nowadays High Frequency (HF) inverter with a compact size is available and widely used.

5.5 Selection of Inverter Based on Operational Perspective

In order to assess the inverter's performance in terms of operational perspective, a literature review and collection of secondary information was carried out by the authors. For the analysis purpose, information of about 200 models of different inverters with different capacity and types were collected. The following sections bring the findings from that survey.

5.5.1 Features of Grid Connectivity

The distributed or off-grid inverter should have the feature for grid connectivity (both incoming and outgoing) so that these solar PV systems would not be completely obsolete when grid extension reaches. With the massive plan of conventional rural electrification, it is always wise to select an inverter having grid connectivity features from the beginning with some incremental cost than completely changing the inverters later on with a high replacement cost.

5.5.2 AC Voltage and Frequency Range

For the standard values, the inverter can be operated substantially without any problems within the tolerance of $+10\ \%$ and $-15\ \%$ for the voltage, and ±0.4 to $1\ \%$ for the frequency, specified by the grid standards of any country. For example, in India, where the single phase AC line is specified as 230 V, 50 Hz, the inverter should work at any voltage value between 253 and 198 V and any frequency value between 49.5 and 50.5 Hz without any problem. Any inverter which does not have this wide range, might not be considered, particularly for distributed power system, which are installed in relatively remote and rural locations, where wide fluctuation of voltage and frequency is prevalent [2].

5.5.3 Operational DC Voltage Range

The operable range of the DC voltage differs according to rated power of the inverter, rated voltage of the AC utility grid system, and design policy. In this survey, the operable range of the DC voltage for a capacity in the range of 180–500 W includes 14–35 V, 30–60 V. Similarly, the operable DC voltage range for a capacity of 10 kW or over includes 330–1,000 V. Hence, depending upon the operational range of the voltage range of the inverter, the capacity and configuration of the solar PV modules should be decided. So, while designing or designing the capacity of the solar PV system, this is one criterion that decides how many modules need to be connected in series or parallel to get the required DC operating voltage.

5.5.4 AC Harmonic Current from Inverter

Minimisation of harmonic current production is required as harmonic current adversely affects load appliances connected to the distribution system and can impair load appliances when the harmonic current is increased. The results of this survey show that Total Harmonic Distortion (THD), the total distortion factor of the current normalised by the rated fundamental current of many of the inverter, is

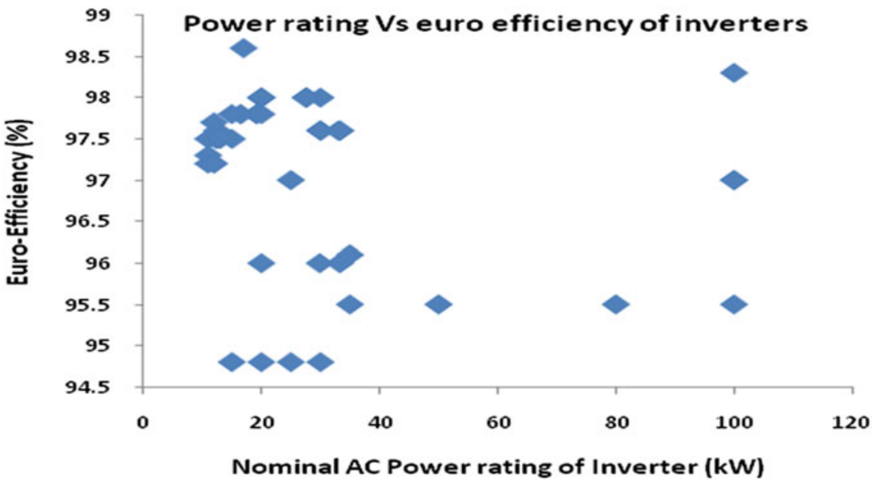

Fig. 8 Power rating versus euro efficiency of inverters

3–5 %. However, there are certain inverters in the power rating of 10–100 kW, that have THD in the range of 1–5 %.

5.5.5 Inverter Conversion Efficiency

Figure 8 presents the performance of a range of inverters.

Figure 8 shows that the efficiency range for all the inverters varies from 94.5 to 98.7 % [5]. In the medium scale range (10–20 kW), there are several inverters available with the euro efficiency range of 97–98 % and the incremental cost of these inverters are not much more than that of the low efficiency inverters (generally USD 50/kW). Thus, the project designer can evaluate the cost versus benefit of the inverter in terms of the enhanced efficiency.

5.5.6 Operational Environment

The installation conditions of the inverter (the indoor installation specification or the outdoor installation specification), the ambient temperature, the requirements for water- and dust-proofing, actual audible noise level of the inverter, and applicable regulations for EMC (electro-magnetic compatibility) needs to be examined carefully. As per the survey (Fig. 9), the maximum acceptable ambient temperature at nominal AC power is in the range of 40–75 °C. This range is relatively wider for 10–40 kW inverter, whereas it is narrower in the operational range of 40–50 °C for larger inverters.

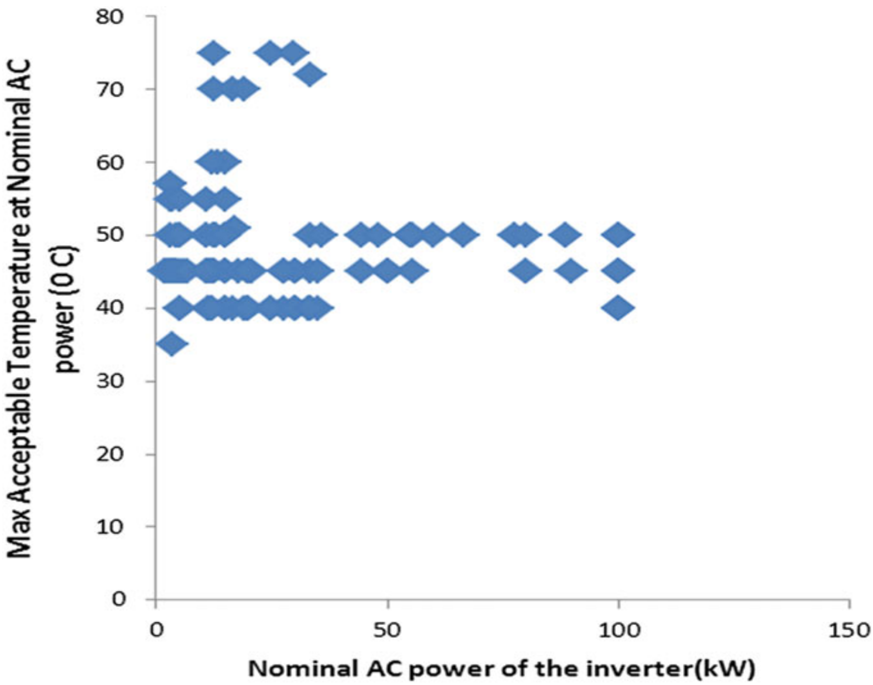

Fig. 9 Maximum acceptable temperature at nominal AC power

5.5.7 Required Protection Devices or Functions

Protective functions include protection for the DC- and the AC-sides. The protective functions for the DC side include those for DC overpower, DC overvoltage, DC undervoltage, DC overcurrent, and detection of DC grounding faults. Protective functions for the AC side include AC overvoltage, AC undervoltage, AC overcurrent, frequency increase, frequency drop, and detection of AC grounding, etc. Most of the inverters include these basic protections.

5.5.8 Standby Power Consumption

The standby power consumption of the inverter is a very important parameter that needs to be checked, particularly for off-grid PV applications where the only source for providing power is PV. So, by practice the lesser the standby power consumption is, the better it is for distributed PV applications. As per Fig. 10, it is observed that there is a wide range of products that are available with normalised standby power consumption for inverter capacity of less than 20 kW. So, the

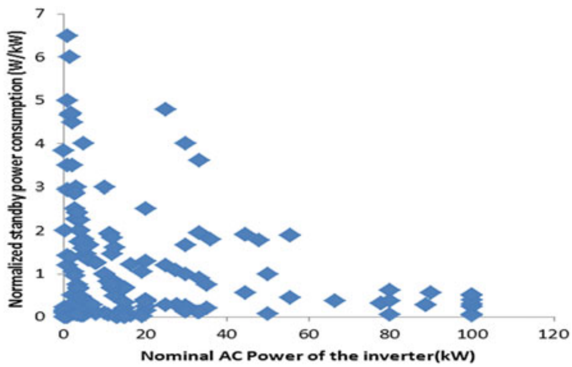

Fig. 10 Normalized standby power consumption of a selection of inverters

inverter can be judiciously selected so that self-consumption of these devices would not be significant.

5.5.9 Inverter System Cost, Size and Weight

The cost of the inverter system is very crucial when considering the economy of a photovoltaic power system. Although the cost of the inverter varies from country to country as well as with make and model, the average cost range of the inverter is found to be USD 600–1,000 per kW [5]. The weight of the inverter system differs considerably according to presence/absence of the isolating transformer (shown in Fig. 11). However, from the project developer's point of view it is a very critical parameter to judge as the weight of system affects the total transportation, handling and installation costs. For an inverter for a household PV power system, weight reduction is important when the inverter is installed indoors or it is to be mounted and thus an appropriate inverter with lower weight should be preferred.

5.5.10 System Guarantee

System guarantee plays a crucial role as it influences the entire system economics. Although the cost data for each of the inverter is not available, it is noted that there are some inverters that are available with an extended guarantee of 25 years.

6 Conclusion

Although PV systems are not technologically new, they have received increased attention because of their ability to meet peak power demand, provide backup power, offer improved power quality and reliability to micro-grids and rural

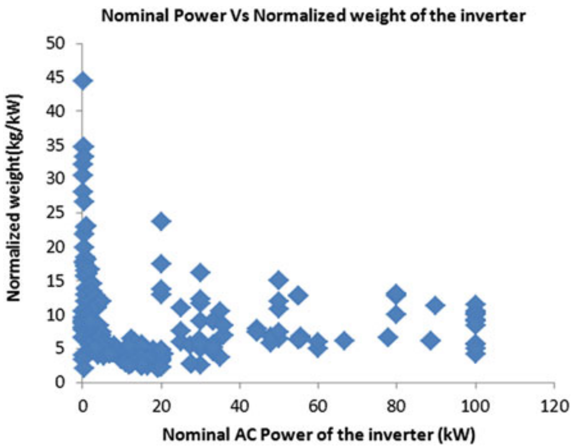

Fig. 11 Normalized weight of different inverters

electrification projects and substantial cost reduction of the PV systems in the last few years. The PV systems require specific power electronic converters to convert the power generated into useful power that can be directly interconnected with the utility grid and/or can be used for specific consumer applications locally. The roles of these power converters become very critical, particularly when it is used in one of the relatively expensive energy generating sources such as PV. With the advent of few state-of-the-art power converters and inverters certain smart design approaches has been possible, which is explained in this chapter. This chapter shows that if the smart design approaches, such as load profiling, load categorisation, and resource profiling, are carried out properly then the total capacity and thus the cost of the system can be reduced substantially. The chapter also shows if the battery and inverter are chosen properly, substantial cost savings in terms of reduced but appropriate PV system sizing can be achieved.

References

1. Antony F, Durschner C, Remmers K-H (2007) Photovoltaic for professionals—solar electric systems marketing, design and installation. Solarpraxis AG Publishers, Earthscan, London
2. Kim H, Kim J, Min B, Yoo D, Kim H (2009) A highly efficient PV system using a series connection of DC–DC converter output with a photovoltaic panel. Renewable Energy 34(11):2432–2436
3. Lasnier F, Ang TG (1990) Photovoltaic engineering handbook. IOP Publishing, Pennsylvania
4. Mohanty P (2008) Solar photovoltaic technology-renewable energy engineering and technology. TERI Publication, India
5. Photon International (2012) July and August issue 2012
6. Kjaer S, Pedersen J, BlaaBjerg F (2005) A review of single phase grid connected inverters for photovoltaic modules. IEEE Trans Indus Appl 41(5):1292–1306
7. Tang Y, Zhao L (2010) Maximum power point tracking techniques for photovoltaic array. New Energy, June 2010, pp 48–51