Design and Sizing of Solar Photovoltaic Systems

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DESIGN AND SIZING OF SOLAR PHOTOVOTAIC SYSTEMS

Photovoltaic (PV) systems (or PV systems) convert sunlight into electricity using semiconductor materials. A photovoltaic system does not need bright sunlight in order to operate. It can also generate electricity on cloudy and rainy days from reflected sunlight.

PV systems can be designed as Stand-alone or grid-connected systems.

A "stand-alone or off-grid" system means they are the sole source of power to your home, or other applications such as remote cottages, telecom sites, water pumping, street lighting or emergency call box on highways. Stand-alone systems can be designed to run with or without battery backup. Battery backup system store energy generated during the day in a battery bank for use at night. Stand-alone systems are often cost-effective when compared to alternatives such as utility line extensions.

A "grid-connected "system work to supplement existing electric service from a utility company. When the amount of energy generated by a grid- connected PV system exceeds the customer's loads, excess energy is exported to the utility, turning the customer's electric meter backward. Conversely, the customer can draw needed power from the utility when energy from the PV system is insufficient to power the building's loads. Under this arrangement, the customer's monthly electric utility bill reflects only the net amount of energy received from the electric utility.

Benefits of PV Systems

a. **Environmentally friendly** - It has zero raw fuel costs, unlimited supply and no environmental issues such as transport, storage, or pollution. Solar power systems produce no air or water or greenhouse gases and produce no noise. Solar systems are generally far safer than other distributed energy systems, such as diesel generators and as such are the most suitable technology for urban on-site generation. PV is the only commercially available renewable technology generation option for urban areas.

b. **Reliability** - With no fuel supply required and no moving parts, solar power systems are among the most reliable electric power generators, capable of powering the most sensitive applications, from space satellites to microwave stations in the mountains and other remote harsh environments. Solar panels typically carry warranties of 20 years or more.

c. **Scalable and modular**- Solar power products can be deployed in many sizes and configurations and can be installed on a building roof or acres of field; providing wide power-handling capabilities, from microwatts to megawatts. The installation is quick and expanded to any capacity.

d. **Universal Applications** - Solar PV is the only renewable energy technology that can be installed on a truly global scale because of its versatility and because it generates power under virtually all conditions, i.e. even in overcast light conditions

e. **Peak Shaving** - Have a rapid response achieving full output instantly. The output of solar systems typically correlates with periods of high electricity demand where air conditioning systems create peak demands during hot sunny days. PV can shave peak-load demand, when energy is most constrained and expensive and therefore can move the load off the grid and alleviate the need to build new peak generating capacity.

f. **Dual use** - Solar panels are expected to increasingly serve as both a power generator and the skin of the building. Like architectural glass, solar panels can be installed on the roofs or facades of residential and commercial buildings.

g. **Low Maintenance Cost** - It is expensive to transport materials and personnel to remote areas for equipment maintenance. Since photovoltaic systems require only periodic inspection and occasional maintenance, these costs are usually less than with conventionally fuelled equipment alternatives.

h. **Cost advantages** - Solar power systems lower your utility bills and insulate you from utility rate hikes and price volatility due to fluctuating energy prices. They can be used as building materials. They can increase character and value of the building. Purchase of a solar power system allows you to take advantage of available tax and financial incentives.

Challenges

The main challenges or constraints to approach PV project are:

a. Budget constraints: Build a system within your target budget.
b. Space constraints: Build a system that is as space efficient as possible.
c. Energy offset: Build a system that offsets a certain percentage of your energy usage.

Design Constraints

Design constraints are the key to the system's successful outcome. They provide clear direction and reduce the scope of economic and system analyses and should be continually referenced throughout the design process. Typical design constraints apply to any system and are modified, expanded, and "personalized" for a specific application. Some typical questions inherent in design constraints are:

a. Will the system output be AC or DC or both?
b. How pure must the electricity be for the load?
c. Will the thermal energy generated be used?
d. How much of the electric- or thermal-load profile can be economically matched with the available area?
e. Is a utility interface available at the location?
f. Will there be unavoidable shadow?
g. Will the system be actively cooled?
h. Will the collectors be flat plate or concentrating?

i. Will the collectors be fixed or tracking?

j. Does the work proposal specify a type of system or specific design feature?

The 6-hour course covers fundamental principles behind working of a solar PV system, use of different components in a system, methodology of sizing these components and how these can be applied to building integrated systems. It includes detailed technical information and step-by-step methodology for design and sizing of off-grid solar PV systems.

The information presented is aiming to provide a solid background and good understanding of the design. The course will be beneficial to electrical & mechanical engineers, energy & environment professionals, architects & structural engineers and other professionals looking to enter solar industry, or interact with solar projects in current line of work.

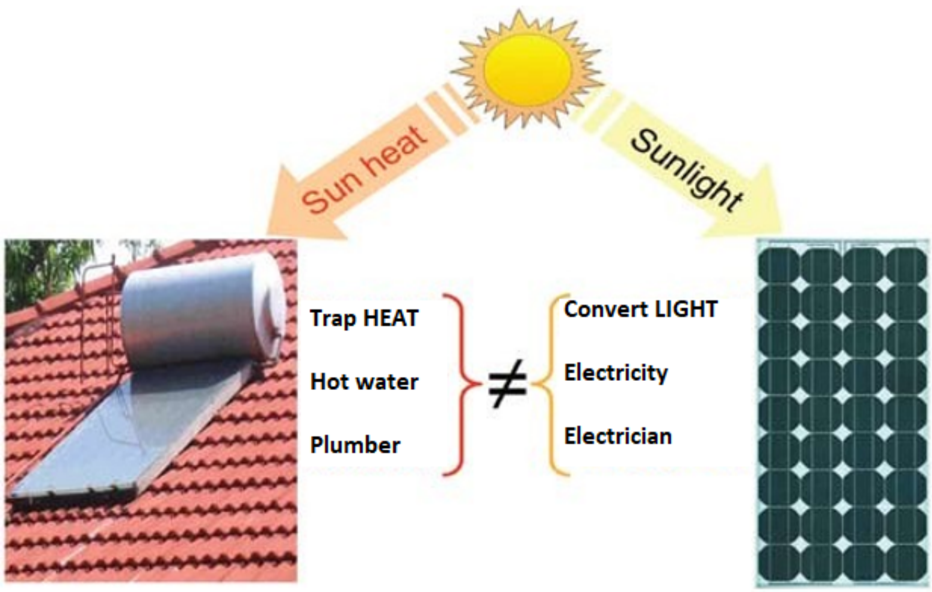
CONTENTS

CHAPTER - 1

PHOTOVOLTAIC (PV) TECHNOLOGY

1.0. SOLAR ENERGY

The sun delivers its energy to us in two main forms: heat and light. There are two main types of solar power systems, namely, solar thermal systems that trap heat to warm up water and solar PV systems that convert sunlight directly into electricity as shown in Figure below.



Difference between Solar Thermal and Solar PV Systems

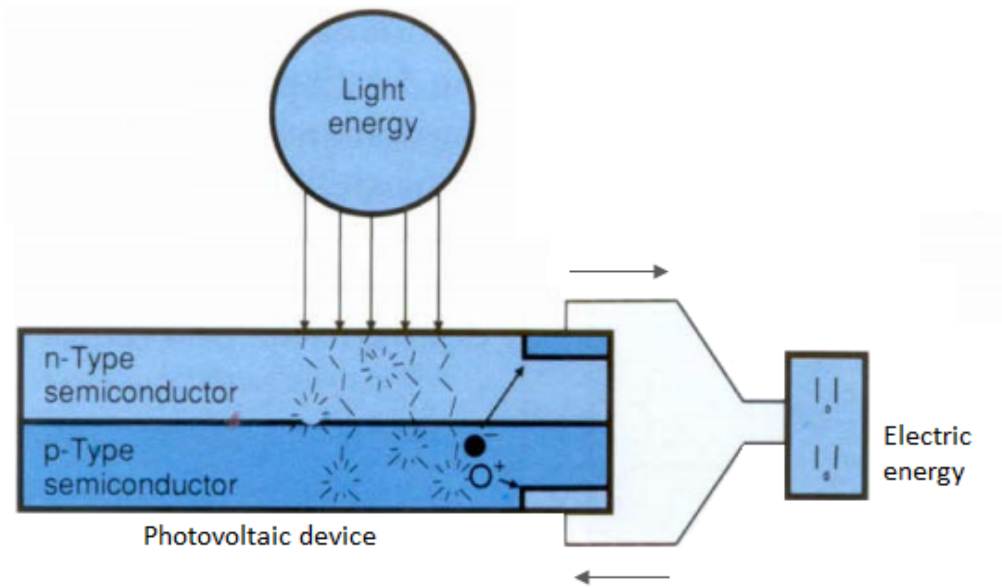
The word photovoltaic comes from “photo,” meaning light, and “voltaic,” which refers to producing electricity. And that's exactly what photovoltaic systems do -- turn light into electricity!

Direct or diffuse light (usually sunlight) shining on the solar cells induces the photovoltaic effect, generating DC electric power. This DC power can be used, stored in a battery system, or fed into an inverter that converts DC into alternating current “AC”, so that it can feed into one of the building’s AC distribution boards (“ACDB”) without affecting the quality of power supply.

Important thing to note is that we are not concerned about the heat content of sunlight; PV cells and modules do not utilize the heat, only the light. When the source of light is not the sunlight then the photovoltaic cell is used as the photo detector. The example of the photo detector is the infra-red detectors.

1.1 PV Technology

The basic unit of a photovoltaic system is the photovoltaic cell. Photovoltaic (PV) cells are made of at least two layers of semiconducting material, usually silicon, doped with special additives. One layer has a positive charge, the other negative. Light falling on the cell creates an electric field across the layers, causing electricity to flow. The intensity of the light determines the amount of electrical power each cell generates.

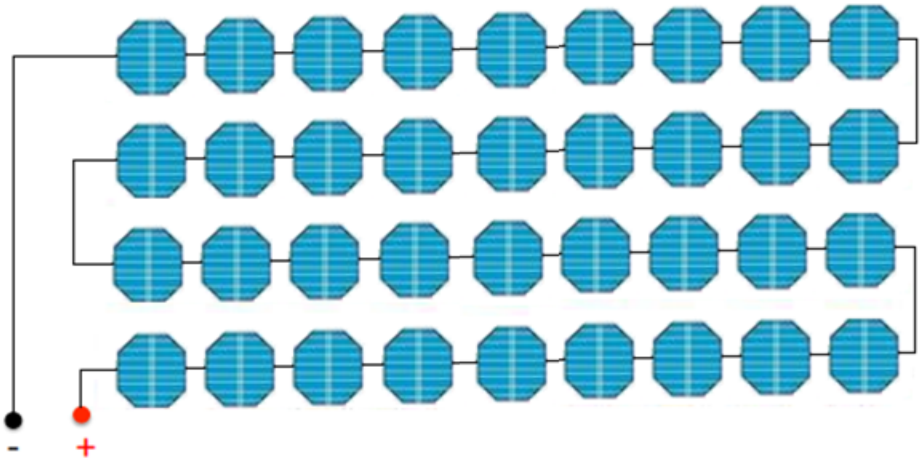


Note that PV cell is just a converter, changing light energy into electricity. It is not a storage device, like a battery.

1.1.1. Solar Cell

The solar cell is the basic unit of a PV system. A typical silicon solar cell produces only about 0.5 volt, so multiple cells are connected in series to form larger units called PV modules. Thin sheets of EVA (Ethyl Vinyl Acetate) or PVB (Polyvinyl Butyral) are used to bind cells together and to provide weather protection. The modules are normally enclosed between a transparent cover (usually glass) and a weatherproof backing sheet (typically made from a thin polymer or glass). Modules can be framed for extra mechanical strength and durability.

Usually 36 solar cells are connected to give a voltage of about 18V. However, the voltage is reduced to say 17V as these cells get hot in the sun. This is enough to charge 12V battery. Similarly, a 72 cells module produces about 34V (36V - 2V for losses), which can be used to charge a 24V battery.



V_{oc} = 0.50 x 36 = 18V DC

Cells are connected in series to make a PV module

A 12-volt battery typically needs about 14 volts for a charge, so the 36-cell module has become the standard of the solar battery charger industry.

The most common cells are 12.7 x 12.7 cm (5 x 5 inches) or 15 x 15 cm (6 x 6 inches) and produce 3 to 4.5 W – a very small amount of power.

The typical module size is 1.4 to 1.7 m² although larger modules are also manufactured (up to 2.5 m²).

1.1.2. PV String

Individual modules can be connected in series, parallel, or both to increase either output voltage or current. This also increases the output power. When number of modules is connected in series, it is called a PV string.

In series connection, the negative terminal of one module is connected to the positive terminal of the next module. In series connections, voltage adds up and the current remain constant.

$V_{Total} = V1 + V2 + \ldots + Vn$

$I_{Total} = I1 = I2 = \ldots = In$

For example, if 10 modules of 12 V and 3-amp rating are connected to make one string, then the total voltage of the string will be 120 V and the total current will be 3- amp.

Reverse happens when modules are connected in parallel. In parallel connection, current adds up and voltage remains constant.

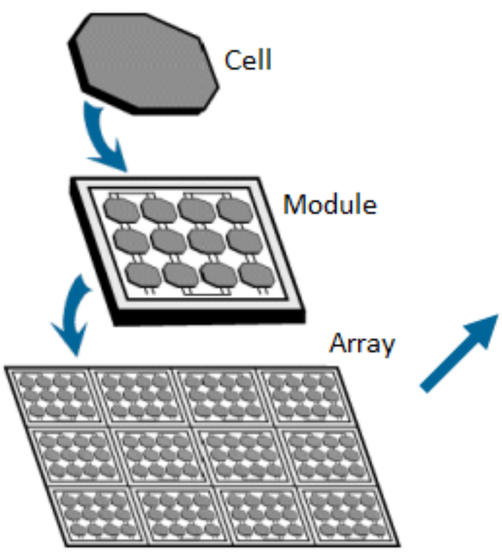
$V_{Total} = V1 = V2 = ... = Vn$

$I_{Total} = I1 + I2 + ... + In$

1.1.3. PV Array

Multiple PV strings are connected in parallel to form a Solar Array. Parallel connection increases the current, while voltage remains the same.

The power that one module can produce is seldom enough to meet requirements of a home or a business, so the modules are linked together to form an array. Most PV arrays use an inverter to convert the DC power produced by the modules into alternating current that can plug into the existing infrastructure to power lights, motors, and other loads. The modules in a PV array are usually first connected in series to obtain the desired voltage; the individual strings are then connected in parallel to allow the system to produce more current. Solar arrays are typically measured by the electrical power they produce, in watts, kilowatts, or even megawatts.



1.2 PV Materials

The vast majorities of commercially available PV modules are made from silicon, which is one of the earth's most abundant elements in the Earth's crust (after oxygen). Silicon's natural properties as a semiconductor are modified by two other elements, boron and phosphorus to create a permanent imbalance in the molecular charge of the material.

a. 85 % of solar cell market
b. Life expectancy of >30 years
c. Energy payback in 2-8 years (positive)

1.3 PV Types

The three general types of photovoltaic cells made from silicon are:

a. Mono-crystalline Silicon – also known as single-crystal silicon
b. Poly-crystalline Silicon – also known as multi-crystal silicon
c. Thin Film Silicon

1.3.1. Crystalline Cells

Crystalline photovoltaic cells are made from silicon which is first melted, and then crystallized into ingots or castings of pure silicon. Thin slices of silicon called wafers, are cut from a single crystal of silicon (Mono-crystalline) or from a block of silicon crystals (Poly-crystalline) to make individual cells. The conversion efficiency for these types of photovoltaic cell ranges between 10% and 20%. Crystalline photovoltaic cells represent about 90% of the market today.

Crystalline cells are divided into two categories:

a. Monocrystalline silicon cells
b. Polycrystalline silicon cells

1.3.2. Monocrystalline PV

Monocrystalline cell comes from a single crystal ingot of high purity, with typical dimensions of 12.5 or 15 cm. The ingot has a cylindrical shape, which is cut into thin slices and made round, semi-round or square shapes. These cells are the most electrically efficient, which means they require less surface area than other cell types to produce an equivalent amount of power. They also have a wide range of transparency options. Disadvantages are their higher costs, requirement for ventilation in order to maximize performance, and a distinctive geometric pattern. Monocrystalline cells are especially suitable for atrium roofs; partial vision glazing in façades, rooftop installations in houses and commercial sun shading or rooftop retrofits where installation area is limited and maximum electricity generation is desired. Commercial module efficiencies range around 14-19%.

1.3.3. Polycrystalline PV

Polycrystalline silicon cells are formed by casting in a cuboid form ingot. The ingot is cut into bars and sliced into thin wafers (a thin sheet of semiconductor material), which in turn are used to create the cells. These cells are less efficient than monocrystalline; however the lower cost per unit area and their distinctive appearance make them a popular choice for relatively large, opaque installations. They have been used extensively in façade spandrel panels and sun shading elements on commercial buildings.

Polycrystalline silicon differs from monocrystalline in terms of cost (due to the reduction of losses) and efficiency (due to the grain boundaries). The difference is small, but still leads to the need for larger cells (21 x 21cm) in order to reach the same efficiency levels. Commercial module efficiencies range around 12-15%.

Important: Ventilation

Crystalline PV technologies should be ventilated over the back of the module to increase their performance. This is because crystalline PV cells operate better under lower temperatures and ventilation allows heat, which is the by-product of energy generation, to be stripped away. New hybrid systems that capture this heat for other uses and improve PV performance are being developed and referred to as PV-T or PV Thermal systems.

Poly Crystalline **Mono Crystalline**

Crystalline cells turn between 14 and 22% of the sunlight that reaches them into electricity.

1.3.4. Thin-Film PV

Thin film photovoltaics are produced by printing or spraying a thin semiconductor layer of PV material onto a glass, metal or plastic foil substrate. By applying these materials in thin layers, the overall thickness of each photovoltaic cell is substantially smaller than an equivalent cut crystalline cell, hence the name “thin film”. As the PV materials used in these types of photovoltaic cells are sprayed directly onto a glass or metal substrate, the manufacturing process is therefore faster are cheaper making thin film PV technology more viable for use in a home solar system as their payback time is shorter.

However, although thin film materials have higher light absorption than equivalent crystalline materials, thin film PV cells suffer from poor cell conversion efficiency due to their non-single crystal structure, requiring larger sized cells. Semiconductor materials used for the thin film types of photovoltaic cell include:

a. Cadmium telluride (CdTe)

b. Copper indium diselenide (CIS)

c. Amorphous silicon (a-Si)

d. Thin film silicon (thin film-Si)

Amorphous silicon is in commercial production while the other three technologies are slowly reaching the market. Amorphous silicon cells have various advantages and disadvantages. On the plus side, amorphous silicon can be deposited on a variety of low-cost rigid and flexible substrates such as polymers, thin metals and plastics as well as tinted glass for building integration. However, on the minus side, the main disadvantage of amorphous silicon (a-Si) is its very low conversion efficiency ranging between 6 to 8% when new.

CIGS Thin Film

Of the different types of photovoltaic cell available, amorphous silicon has the highest light absorption of over 40 times higher than crystalline silicon. The advantage of this is that a much thinner layer of amorphous silicon material is required to make a thin film PV cell reducing manufacturing costs and price. Just to give a brief impression of what "thin" means, in this case, we're talking about a thickness of 1 micrometer. With only 6 to 7% efficiency rate, these cells are less effective than crystalline silicon ones— but in current scenario, while a larger surface area is required for output, the cost of electricity per Watt peak is currently more attractive.

1.3.5. Third-Generation PV

The 3rd generation PV technology includes multi-junction PV and concentrator PV Cells.

Multi-junction PV cells are designed to maximize the overall conversion efficiency of the cell by creating a multi-layered design in which two or more PV junctions are layered one on top of the other. The cell is made up of various semiconductor materials in thin-film form for each individual layer. The advantage of this is that each layer extracts energy from each photon from a particular portion of the light spectrum that is bombarding the cell. This layering of the PV materials increases the overall efficiency and reduces the degradation in efficiency that occurs with standard amorphous silicon cells.

Concentrator photovoltaic's (CPV) utilizes lenses to focus sunlight on to solar cells. The cells are made from very small amounts of highly efficient, but expensive, semi-conductor PV material (generally gallium arsenide or GaA). CPV systems use only direct irradiation. They are most efficient in very sunny areas which have high amounts of direct irradiation. The modules use precise and accurate sets of lenses permanently oriented towards the Sun. This is achieved using a double-axis tracking system. Efficiencies of 25 to 30% have been achieved with GaAs, although cell efficiencies well above 40% have been achieved in the laboratory.

Other emerging technologies include:

a. Instead of using solid-state PN-junction technology, an electrolyte, dye sensitized liquid, gel or solid is used to produce a photo-electrochemical PV cell. These types of photovoltaic cells are manufactured using microscopic molecules of photosensitive dye on a nano-crystalline or polymer film.

b. 3d photovoltaic cell uses a unique three-dimensional structure to absorb the photon light energy from all directions and not just from the top as in convectional flat PV cells. The cell uses a 3D array of miniature molecular structures which capture as much sunlight as possible; boosting its efficiency and voltage output while reducing its size, weight and complexity.

These 3rd generation PV technologies currently suffer from low efficiency output and are unable to maintain their performance characteristics beyond three to five years. However, these products have a significant competitive advantage in consumer applications because of the substrate flexibility and ability to perform in dim or variable lighting conditions.

1.4 PV Module Rating

In the solar industry, the peak power rating of a panel is frequently abbreviated as kWp.

kWp is the peak power of a PV module or system that describes the energy output of a system achieved under full solar radiation under set Standard Test Conditions (STC). Solar radiation of 1,000 W/m^2, module temperature of 25°C and solar spectrum air mass of 1.5 is used to define standard conditions. This is generally referred to as a "full sun" condition. That is full irradiance. Less than full sun will reduce the current output of the cell by a proportional amount. For example, if only one-half of the sun's energy (500 W/m^2) is available, the amount of output current is roughly cut in half because the solar cell only has half the brightness to generate electricity.

STC conditions are:

a. 1,000W/m^2 of sunlight (solar irradiance, often referred to as peak sunlight intensity, comparable to clear summer noon time intensity)
b. 25°C cell temperature
c. Spectrum at air mass of 1.5 --- (solar spectrum as filtered by passing through 1.5 thickness of atmosphere (ASTM Standard Spectrum).

A manufacturer may rate a particular solar module output at 100 Watts of power under STC and call the product a "100-watt solar module." This module will often have a production tolerance of +/-5% of the rating, which means that the module can produce 95 Watts and still be called a "100-watt module." To be conservative, it is best to use the low end of the power output spectrum as a starting point (95 Watts for a 100-watt module).

1.4.1. Module Efficiency

The efficiency of each PV product is specified by the manufacturer. Efficiencies range from as low as 5% to as high as 15%–19%. A technology's conversion efficiency rate determines the amount of electricity that a commercial PV product can produce. For example, although thin-film amorphous silicon PV modules require less semiconductor material and can be less expensive to manufacture than crystalline silicon modules, they also have lower conversion efficiency rates. These will need close to twice the space of a crystalline silicon PV array because its module efficiency is halved, for the same nominal capacity under Standard Test Conditions (STC).

The conversion efficiency of different PV cell technologies is summarized in Table below.

Conversion efficiencies of various PV module technologies

PV type	Description (Color and texture)	Module efficiency	Surface area for 1kWp system (m^2)
Monocrystalline (m-Si)	Blue, grey, black, high light absorption	14-19%	7
Polycrystalline (p-Si)	Bright bluish speckled tone	12-15%	9
Thin film Amorphous silicon	Reddish-black, very flexible/durable	6-8%	17

PV type	**Description (Color and texture)**	**Module efficiency**	**Surface area for 1kWp system (m^2)**
(a-Si)			
Thin film CIGS/ CIS (Copper Indium Gallium Selenide/ Copper Indium Selenide)	Black, shiny cell – flexible or rigid	9-12%	11
Thin film CdTe (Cadmium telluride)	Grey-green rigid cell	7-10%	14
Titanium dioxide (TiO2) dye	Light brown translucent window system	3-5%	20

Notes:

Each technology has an associated range of output in watts per square foot or per square meter and cost per watt. For example:

a. PV Modules with higher efficiency will have a lower surface area for equivalent watts. Installation and racking costs will be less with more efficient modules, but this must be weighed against the higher cost.

b. Crystalline silicon panels have higher electricity outputs per square meter, but greater costs and design constraints. The power output of single-crystalline and poly-crystalline modules is almost similar.

c. Thin film amorphous silicon modules have lower rated efficiencies than crystalline silicon modules, but these are less expensive and may be integrated more easily onto the irregular surfaces. Data also suggests that in cloudy weather, all thin film types tend to perform better than crystalline silicon.

d. The capacity of the PV system is physically limited to the dimensions of the building's available surface area. The balance between the amount of power required and the amount of surface area available can determine the type of PV technology that will be used.

1.5 PV System Components

The key parts of a solar PV energy generation system are:

a. Photovoltaic array to collect sunlight

b. An inverter to transform direct current (DC) to alternate current (AC)

c. A set of batteries and charge controller for stand-alone PV systems

d. Other system components.

All system components, excluding the PV modules, are referred to as the balance of system (BOS) components.

Components of PV System

1.5.1. PV Array

A PV Array is made up of PV modules, which are environmentally-sealed collections of PV Cells— the devices that convert sunlight to electricity. The most common PV module that is 5- to 25 square feet in size and weighs about 3-4 lbs/ft^2.

Often sets of four or more smaller modules are framed or attached together by struts in what is called a panel. This panel is typically around 20-35 square feet in area for ease of handling on a roof. This allows some assembly and wiring functions to be done on the ground if called for by the installation instructions.

1.5.2. Batteries

Battery stores electric power for operation during nighttime or during extended periods of cloudy or overcast weather when the PV array by itself cannot supply enough power. The number of days the battery storage capacity is available to operate the electrical loads directly from the battery, without any energy input from the PV array is called days of "autonomy" in a standalone PV system. For common, less critical PV applications, autonomy periods are typically designed for between two and six days. For critical applications involving essential loads or public safety autonomy periods may be greater than ten days.

Lead-acid or lithium-ion batteries are typically used.

1.5.3. Inverter

The photovoltaic array and battery produce DC current and voltage. The purpose of an inverter is to convert the DC electricity to AC electricity used by your electrical appliances and/or exportable to the AC grid. The typical low voltage (LV) supply into a residential or small commercial building will be either 120V AC single phase or 408V AC three phase.

Inverters are offered in a wide range of power classes ranging from a few hundred watts (normally for stand-alone systems), to several kW (the most frequently used range) and even up to 2,000 kW central inverters for large-scale systems.

1.5.4. Charge Controller

Batteries are connected to the PV array via a charge controller. The charge controller protects the battery from overcharging or discharging. It can also provide information about the state of the system or enable metering and payment for the electricity used.

1.5.5. Balance of System (BOS)

In addition to the PV modules, battery, inverter and charge controller there are other components required in a solar PV microgrid system; these components are referred to as Balance of Systems (BoS) equipment. The most common components are mounting structures, tracking systems, electricity meters, cables, power optimizers, protection devices, transformers, combiner boxes, switches, etc.

CHAPTER - 2

PHOTOVOLTAIC PERFORMANCE

2.0. FACTORS AFFECTING PV MODULE PERFORMANCE

A PV module's performance is directly related to the amount of sunlight it receives. If a PV module is shaded, even partially, its performance will be very poor. There are other factors that affect the output of a solar power system.

These factors need to be understood so that the customer has realistic expectations of overall system output and economic benefits under variable weather conditions over time.

2.1 Environmental Factors

2.1.1. Location

When designing a PV system, location is the starting point. The amount of solar access received by the photovoltaic modules is crucial to the financial feasibility of any PV system. Latitude is a primary factor.

2.1.2. Solar Irradiance

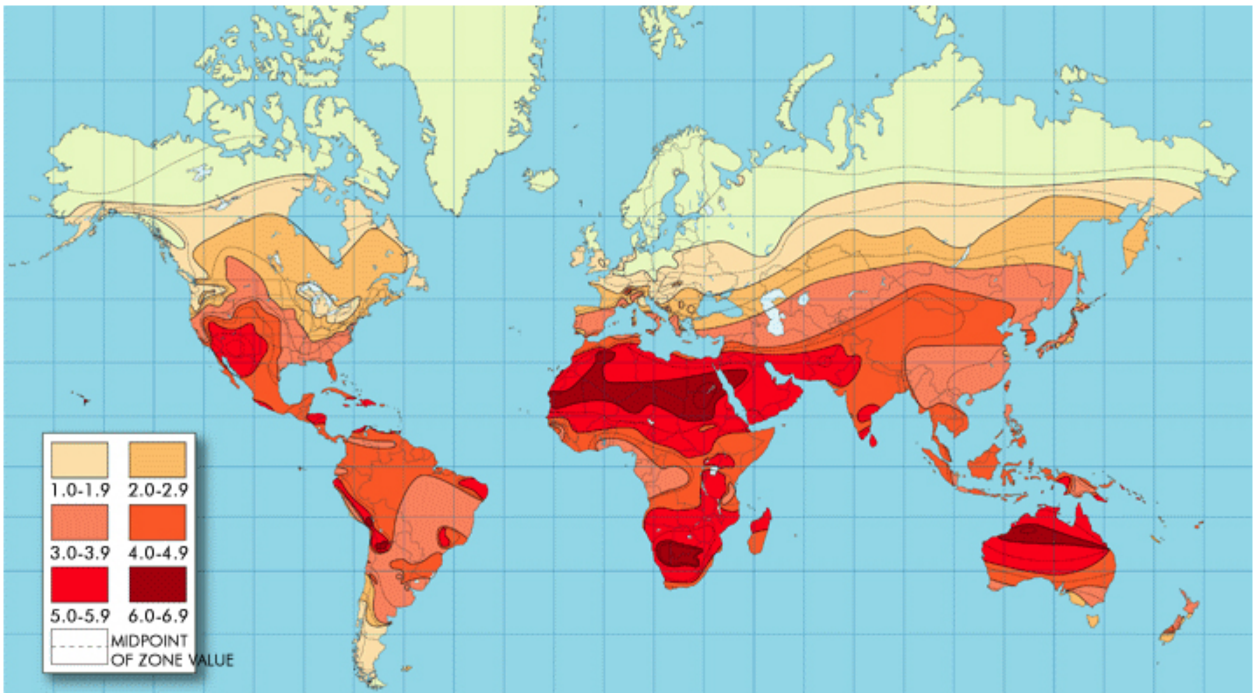
It is a measure of how much sunlight intensity or power in Watts per square meter falling on a flat surface or you are getting at your location. Because weather conditions are somewhat similar over the years, it is possible to predict the average monthly and annual energy production of a system using historic, standardized weather data. There are maps available of solar resources showing how much energy reaches the surface of panels. The data is presented in standardized maps that show how many standard sunshine hours can be exacted over a month or a year. It expressed by term "solar insolation".

2.1.3. Solar Insolation

Solar insolation is a measure of solar irradiance reaches a PV surface at any given time. Solar energy available in a given location is expressed as $kWh/m^2/day$. This is commonly referred as Peak Sun Hours (PSH). For example, if solar radiation for a location is $5kWh/m^2/day$ then PSH for that location will be 5 hours. Now, if you install 1kW solar panel on that location, it will produce 1kW x 5h = 5kWh energy per day without considering any losses.

More intense sunlight will result in greater module output. Lower sunlight levels result in lower current output. Voltage is not changed appreciably by variations of sunlight intensity.

The map below shows the amount of solar energy in hours, available each day on an optimally tilted surface during the worst months of the year to generate electricity (based on accumulated worldwide solar insolation data). This is very useful because it allows you to calculate the energy generation of your solar system.



Statistical estimations of average daily insolation levels for specific locations are commonly used in the PV design process and measured as kilowatt-hours per square meter per day (kWh/m^2/day).

2.1.4. Electricity Generation V/s the Sun Hours Available per Day

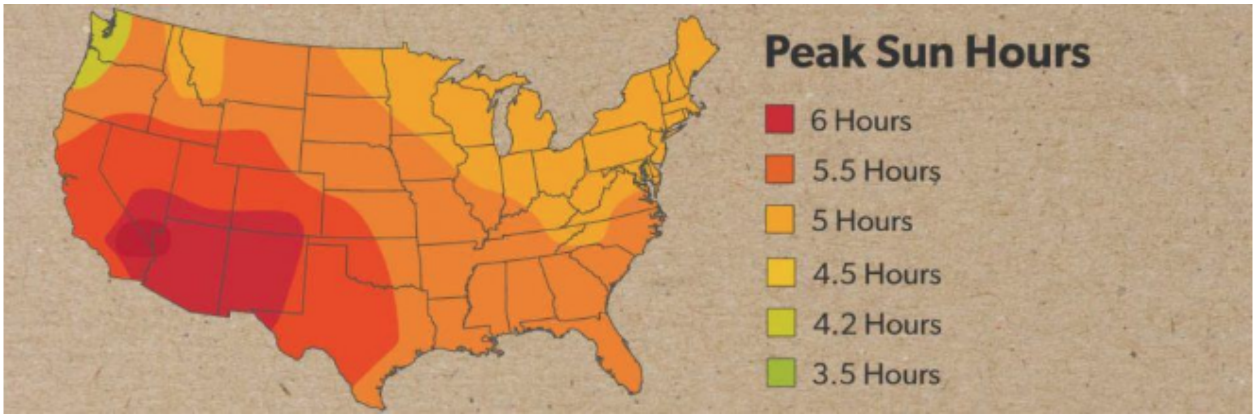
Several factors influence how much sun power your modules will be exposed to:

a. When you will be using your system – summer, winter, or year-round.

b. Typical local weather conditions

c. Fixed mountings vs. trackers

d. Location and angle of PV array



The Annexure-2 at the end of the course provides the sun hour ratings for several cities in North America for summer, winter and year-round average. If you use your system primarily in the summer, use the summer value; if you are using your system year-round, especially for a critical application, use the winter value. If you are using the system most of the year (spring, summer and fall) or the application is not critical, use the average value.

Note that it is more difficult to produce energy during the winter because of shorter days, increased cloudiness and the sun's lower position in the sky.

2.1.5. Air Mass

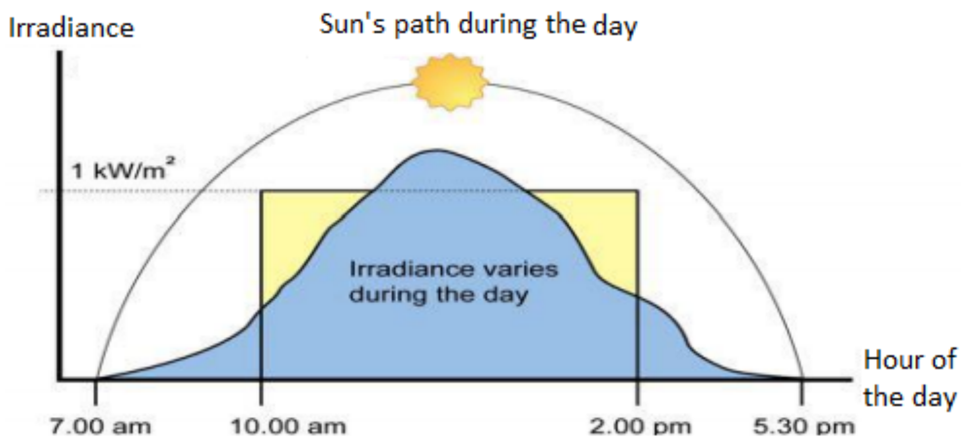
Air mass refers to "thickness" and clarity of the air through which the sunlight passes to reach the modules (sun angle affects this value). The standard is 1.5.

2.1.6. Sun Angle and PV Orientation

The direction that a solar panel faces is referred to as its orientation. The orientation of the solar array is very important as it affects the amount of sunlight hitting the array and hence the amount of power the array will produce. The orientation generally includes the direction the solar module is facing (i.e. due south) and the tilt angle which is the angle between the base of the solar panel and the horizontal. The amount of sunlight hitting the array also varies with the time of day because of the sun's movement across the sky.

Solar modules should be installed so that as much radiation as possible is collected. Ideally, the PV installations on the North of the equator perform optimally when oriented to the South and tilted at an angle 15 degrees higher than the site latitude. If the PV array is mounted on a building where it is difficult for the panels to face the South, then it can be oriented to the East or West but under no circumstances to the North as its efficiency will be then very limited.

The highest efficiency of a PV module or peak power occurs when its surface is perpendicular to the sun's rays. As the rays deviate from perpendicular, more and more of the energy is reflected rather than absorbed by the modules.



Most PV systems are mounted in a fixed position and cannot follow the sun throughout the day. It is possible to improve the output by installing PV modules on trackers to follow the sun from east to west during the day (single-axis trackers), and from north to south during seasonal changes (dual-axis trackers). This can be expensive, so it is not common practice for most PV applications.

PVs should be tilted toward the sun's average elevation, equal to the latitude of the array's location, to capture most of the solar energy throughout a year. For example, a system used throughout the year at latitude of 25° can have a tilt angle of 15° to 35° for maximum amount of electricity over a year.

2.1.7. Shading

Shading may be one of the most important parameters for energy loss in a PV array. Even the partial-shading of one cell of a 36-cell module can reduce the power output significantly.

Potential shading sources can be trees and bushes, neighboring buildings and self-shading by the multiple rows of modules itself. Calculations need to be done to find the minimum distance between PV Array rows to avoid winter mid-day shading.

The general rule of thumb is to locate the array at a distance away from the object that is at least twice the height of the object. This will ensure that the object will not cast a shadow for 4 hours either side of solar noon.

As a rule, with lower tilt angle, there is less shading, and the area can be better exploited. However, in that case, the solar yield drops throughout the year. For this reason, a tilt angle of 15° is usually chosen.

Thin film PV modules are more tolerant to partial shading than crystalline silicon PV modules.

2.2 Electrical Characteristics

The type of solar power produced by a photovoltaic solar cell is called direct current or DC the same as from a battery. Most photovoltaic solar cells produce a “no load” open circuit voltage of about 0.5 to 0.6 volts when there is no external circuit connected. This output voltage (V_{OUT}) depends very much on the load current (I) demands of the PV cell. For example, on very cloudy day the current demand would be low and so the cell could provide the full output voltage, V_{OUT} but at a reduced output current. But as the current demand of the load increases a brighter light (solar radiation) is needed at the junction to maintain a full output voltage, V_{OUT}.

However, there is a physical limit to the maximum current that a single photovoltaic solar cell can provide no matter how intense or bright the suns radiation is. This is called the maximum deliverable current and is symbolized as I_{MAX}. The I_{MAX} value of a single photovoltaic solar cell depends upon the size or surface area of the cell, the amount of direct sunlight hitting the cell, its efficiency of converting this solar power into a current and of course the type of semiconductor material that the cell is manufactured from either silicon, gallium arsenide, cadmium sulphide, cadmium telluride etc.

Most commercially available photovoltaic solar cells have solar power ratings which indicate the maximum deliverable solar power, P_{MAX} that the cell can provide in watts and is equal to the product of the cell voltage V multiplied by the maximum cell current I and is given as:

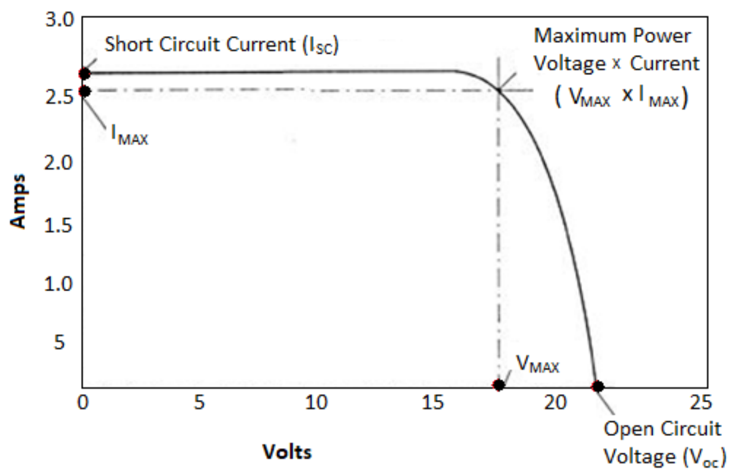
$P_{MAX} = V_{OUT} \times I_{MAX}$

Where: P is in Watts, V is in Volts, and I is in Amperes

Various manufacturers refer to a PV cells output power at full sun as its: “maximum output power”, “peak power”, “rated power”, “maximum power point” or other such terms but they all mean the same.

2.2.1. Photovoltaic I-V Characteristics Curves

Manufacturers of the photovoltaic solar cells produce current-voltage (I-V) curves, which gives the current and voltage at which the photovoltaic cell generates the maximum power output and are based on the cell being under standard conditions of sunlight and temperature with no shading.



Typical Current Voltage Curve of a Photovoltaic Module

Voltage (V) is plotted along the horizontal axis while Current (I) is plotted along the vertical axis.

The available power (W) from the PV, at any point of the curve, is the product of current and voltage at that point.

2.2.2. Short Circuit Current (I_{SC})

A photovoltaic module will produce its maximum current when there is essentially no resistance in the circuit. This would be a short circuit between its positive and negative terminals. This maximum current is called the short circuit current (I_{sc}). This value is higher than I_{max} which relates to the normal operating circuit current.

Under this condition the resistance is zero and the voltage in the circuit is zero.

2.2.3. Open Circuit Voltage (V_{OC})

Open circuit voltage (V_{oc}) means that the PV cell is not connected to any external load and is therefore not producing any current flow (an open circuit condition). This value depends upon the number of PV panels connected in series. Under this condition the resistance is infinitely high and there is no current.

2.2.4. Maximum Power (P_{MAX} or MPP)

This relates to the point where the power supplied by the array that is connected to the load (batteries, inverters) is at its maximum value, where $P_{max} = I_{max} \times V_{max}$. The maximum power point of a photovoltaic array is measured in Watts (W) or peak Watts (Wp).

I_{max} and V_{max} value occurs at the "knee" of the I-V curve.

2.2.5. Fill Factor (FF)

The fill factor is the ratio of maximum power output (P_{max}) to the product of the open-circuit voltage times the short-circuit current, ($V_{oc} \times I_{sc}$). The relationship is:

$$FF = \frac{P_{max}}{V_{oc} \times I_{sc}} = \frac{I_{max} \times V_{max}}{V_{oc} \times I_{sc}}$$

FThe fill factor gives an idea of the quality of the array. The closer the fill factor to 1 (unity), the more power the array can provide. Typical values are between 0.7 and 0.8.

2.2.6. PV Panel Energy Output

You have learnt previously that the power output of a photovoltaic solar cell is given in watts and is equal to the product of voltage times the current (V x I). The optimum operating voltage of a PV cell under load is about 0.46 volts at the normal operating temperatures, generating a current in full sunlight of about 3 amperes. Then the power output of a typical photovoltaic solar cell can be calculated as:

$P = V \times I = 0.46 \times 3 = 1.38$ watts.

Now this may be okay to power a calculator, small solar charger or garden light, but this 1.38 watts is not enough power to do any usable work. However, when the PV cells are connected in series (daisy chained), the voltage is added and when connected in parallel (side-by-side) the current is added. Suitable combination PV modules in series and parallel give you the desired voltage, current and power output.

2.3 PV Module Output

For a specific load, PV module output depends on two major factors:

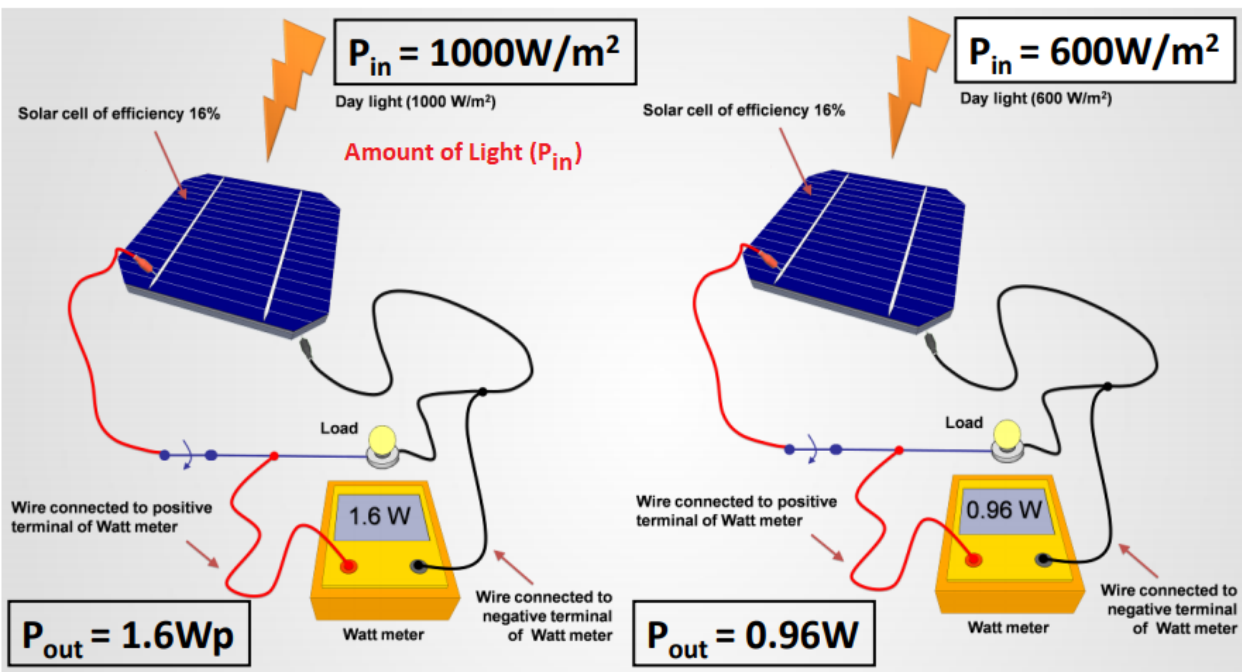
a. Irradiance or light intensity

b. Temperature

2.3.1. Solar Intensity

The amount of sunlight falling onto the face of the PV cell affects its output. The more sunlight entering the cell, the more current it produces. The voltage will remain the same.

Figure below shows that under different test conditions, when day light is 1000 W/m^2 v/s 600 W/m^2, the power out from the PV module varies in proportion.

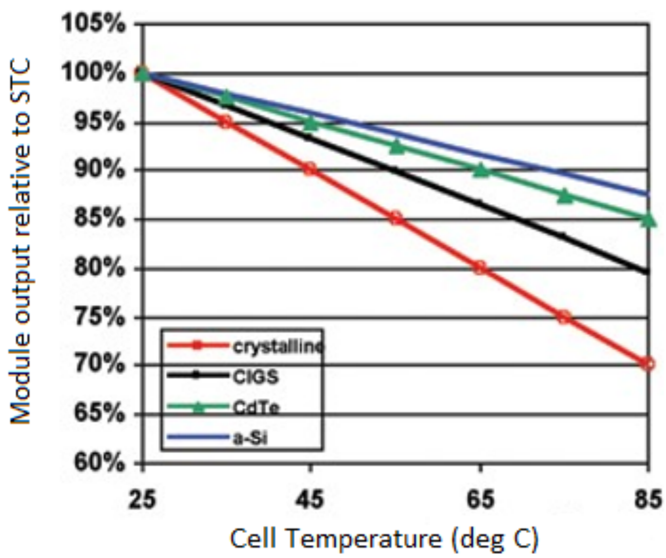


Dirt and dust can accumulate on the solar module surface, blocking some of the sunlight and reducing output. Although, rigorous maintenance will clean off the dirt and dust regularly, it is more realistic to estimate system output considering the reduction due to dust buildup in the dry season. A typical annual dust reduction factor to use is 93% or 0.93. So, the "100- watt module" operating with some accumulated dust may operate on average at about 79 Watts (85 Watts x 0.93 = 79 Watts).

2.3.2. Temperature

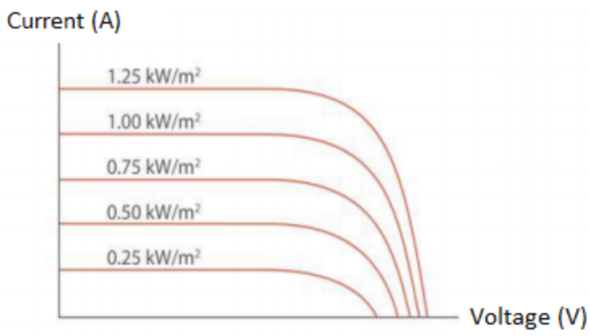
PV cell performance declines at higher cell temperatures. The operating voltage drops with increasing cell temperature. So, in full sun the output voltage reduces by about 5% for every 25°C increase in cell temperature. Then photovoltaic panels with more solar cells are recommended for very hot climates than would be used in colder ones in order to offset power output losses due to high temperatures.

Most thin film technologies have a lower negative temperature coefficient compared to crystalline technologies. In other words, they tend to lose less of their rated capacity as temperature rises. Refer graphical representation below:

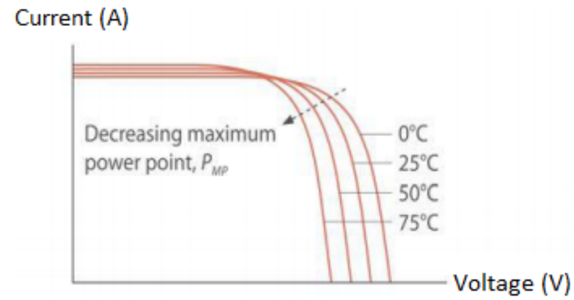


Effects of a negative temperature coefficient of power on PV module performance

As the temperature of a solar cell increases, the open circuit voltage Voc decreases but the short circuit current Isc increases marginally.



I-V Curves at different Light Intensity



I-V Curves at different Temperatures

2.4 PV Module Efficiency & De-rating Factors

PV module efficiency is the ratio of the electrical power output P_{out}, compared to the solar power input P_{in}, hitting the module. P_{out} can be taken to be P_{MAX}, since the solar cell can be operated up to its maximum power output to get the maximum efficiency.

The efficiency of a typical solar array is normally low at around 10-12%.

Example:

On a clear sunny day, a 1kWp PV array received 6 Peak Sun Hours (PSH). Expected output can be determined as follows:

Peak Power Output x Peak Sun Hours = Expected Output

1kW x 6PSH = 6kWh

The calculation above shows the maximum theoretical energy output, which will never be produced in a real PV system. The actual output would be a lot lower than calculated because of inefficiencies of and losses in the PV system. A summary of typical efficiency losses is provided in the table below.

Cause of loss	***Estimated Loss (%)**	**De-rating Factor**
Temperature	10%	0.90
Dirt	3%	0.97
Manufacturer's Tolerance	3%	0.97
Shading	2%	0.95
Orientation/Tilt Angle/Azimuth	1%	0.99
Losses due to voltage drop in cables from PV array to	2%	0.98

battery.		
Losses in distribution cables from PV battery to loads	2%	0.98
Losses in a charge controller	2%	0.98
Battery losses	10%	0.9
Inverter	10%	0.9
Loss due to irradiance level	3%	0.97
Total de-rating factor (multiplying all de-rating factors)		0.60

* Typical losses in PV systems. Actual loss will be as per site conditions

Energy Yield = Peak Sun Hour x Module Rated Power x Total Derating Factor

Example:

On a clear and a sunny day, a 1kWp PV array received 6 Peak Sun Hours. Expected output can be determined as follows:

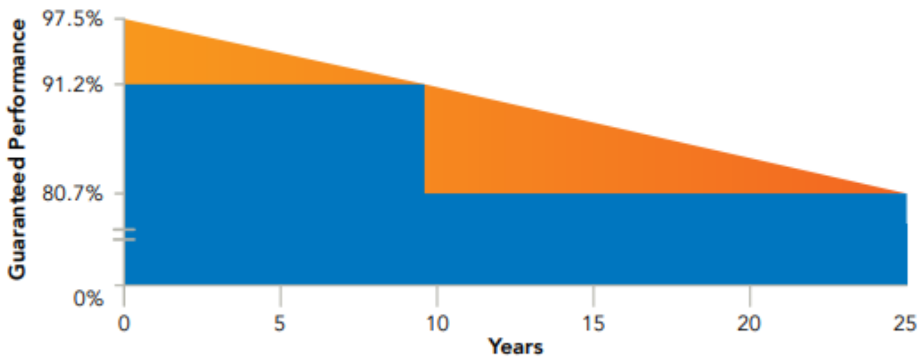
Expected Output = Peak Sun Hours x Peak Power Output x Total derating factor

= 1kWp x 6 x 60%

= 3.6 kWh

2.4.1. Performance degradation over life cycle

The performance of a PV module will decrease over time. The degradation rate is typically higher in the first year upon initial exposure to light and then stabilizes. Factors affecting the degree of degradation include the quality of materials used in manufacture, the manufacturing process, the quality of assembly and packaging of the cells into the module, as well as maintenance levels employed at the site. Generally, degradation of a good quality module is about 20% during the module life of 25 years @ 0.7% to 1% per year.



PV Module Degradation

Example:

On a clear and a sunny day, a 1kWp PV array received 6 Peak Sun Hours (hours). Total loss (de-rating factor) in the system is estimated at 0.70 (70%)

Expected output can be determined as follows:

Expected Output = Peak Sun Hours x Peak Power Output x Total derating factor

= 1kWp x 6 hour/day x 0.70

= 4.2kWh per day (1st year)

Now considering degradation of module as per the indicative profile above (example only, actual degradation of module will be based on module quality and climatic conditions)

Energy generation:

= 3.83kWh per day (on 10th year)

= 3.39kWh per day (on 25th year)

2.5 PV Array Sizing

The equation that may be used to size a stand-alone PV system is:

$$W_{PV} = \frac{E}{PSH \times \eta_{Sys}}$$

- W_{PV} = peak wattage of the array, Wp
- E = daily energy requirement, Wh
- PSH: average daily number of Peak Sun Hours in the design month for the inclination and orientation of the PV array

- η_{Sys} = total system efficiency

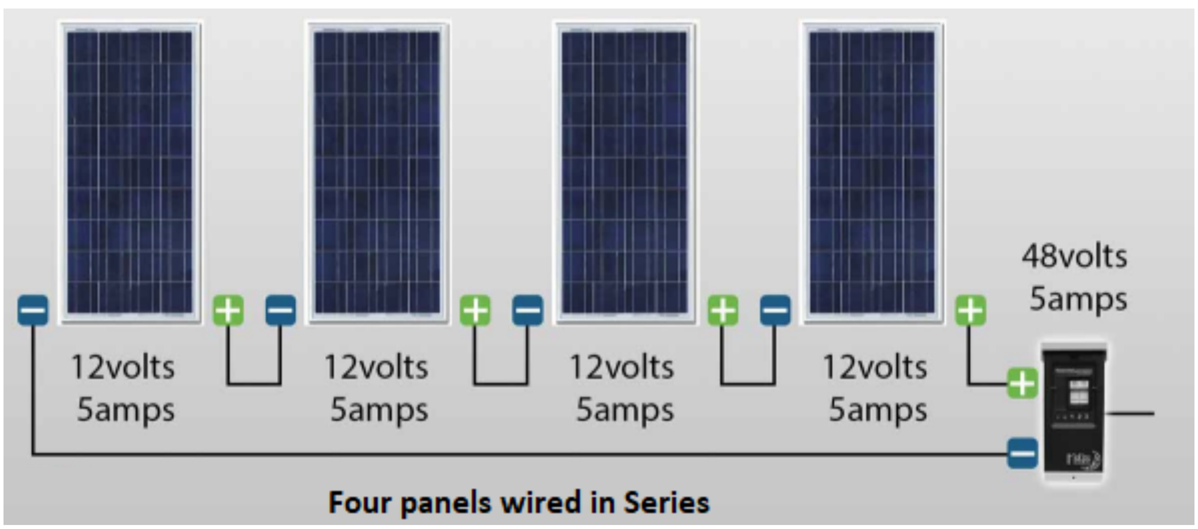
The month that the system is designed is the month of the lowest average daily solar radiation during the operational period of the system.

The number of peak hours is for the inclination and orientation of the PV array. If the only information available is for solar radiation in a horizontal plane, then a tilt and orientation correction factor should be applied.

2.5.1. Wiring Solar Panels in a Series Circuit

Connect the positive terminal of the first solar panel to the negative terminal of the next one.

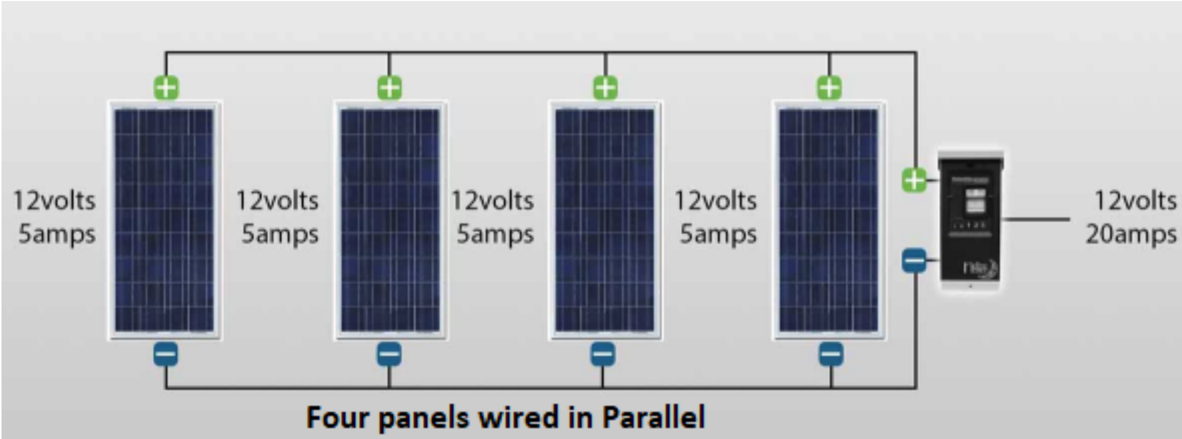
Example: If you had 4 solar panels in a series and each was rated at 12 volts and 5 amps, the entire array would be 48 volts at 5 amps.



2.5.2. Wiring Solar Panels in a Parallel Circuit

Connect all the positive terminals of all the solar panels together, and all the negative terminals of all the panels together.

Example: If you had 4 solar panels in parallel and each was rated at 12 volts and 5 amps, the entire array would be 12 volts at 20 amps.



2.5.3. Rule of Thumb

You will require approximate $10m^2$ surface for 1 kWp power.

2.6 Applicable Codes and Standards

a. NEC Article 690 – Solar Photovoltaic Systems. Article 690 addresses safety standards for the installation of PV systems.

b. Uniform Solar Energy Code – ICC

c. Building Codes – ICC, ASCE 7-05

d. UL Standard 1703, Flat-plate Photovoltaic Modules and Panels

e. IEEE 1547, Standard for Interconnecting Distributed Resources with Electric Power Systems

f. UL Standard 1741, Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources PV Systems and the NEC.

CHAPTER - 3

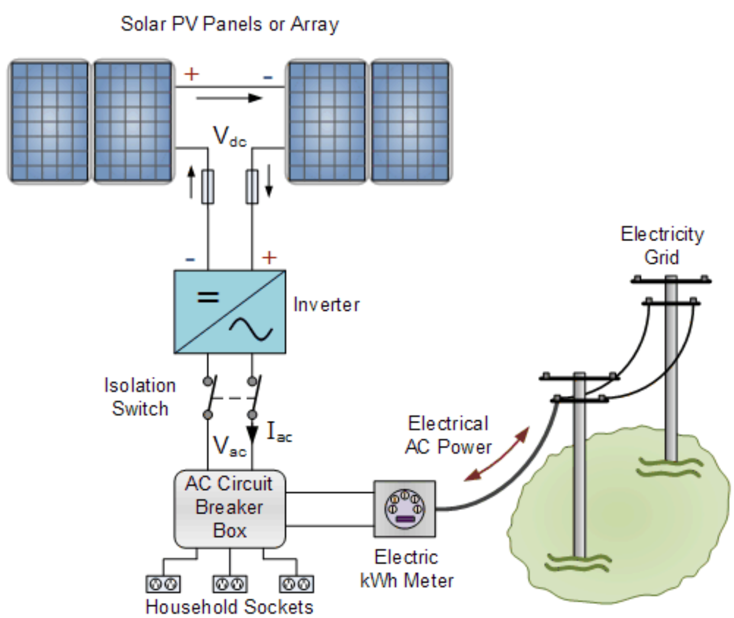
PV SYSTEM CONFIGURATIONS

3.0. SYSTEM CONFIGURATIONS

There are two main configurations of Solar PV systems: Grid-connected (or grid-tied) and Off-grid (or standalone) solar PV systems.

3.1 Grid Connected PV Systems

In a grid-connected PV system, the PV array is directly connected to the grid-connected inverter without a storage battery. If there is enough electricity flowing in from your PV system, no electricity will flow in from the utility company. If your system is generating more power than you are using, the excess will be exported into the energy utility grid, turning your meter backwards. During the times when the PV system isn't producing electricity, such as at night, the power grid will supply all the building's demand. The energy utility company in lieu will provide energy credit to providers based on the solar production. This is called "Net Metering". In this process, energy goes in and out through a single meter.



Grid Connected PV System

Grid-Connected System is the simplest and most cost-effective way to connect PV modules to regular utility power. If utility power is reliable and well maintained in your area, and energy storage is not a priority, you don't necessarily need a battery. But if the utility power goes down, even if there is solar, the PV system will be off for the safety of the utility workers.

The main application of grid connected PV system is in cities, which are well covered by the national power grid. The PV systems are generally installed on buildings on the roof or integrated into the building. The latter is also known as Building Integrated Photovoltaics ("BIPV"). With BIPV, the PV module usually displaces another building component, e.g. window glass or roof/wall cladding, thereby serving a dual purpose and offsetting some costs. The PV systems can be mounted on the ground if land is not a constraint.

3.1.1. Benefits of Grid Connected System

a. A grid-connected system can be an effective way to reduce your dependence on utility power, increase renewable energy production, and improve the environment.
b. System doesn't always require covering all electrical needs
c. Requires less surface area for panels and no batteries
d. Less expensive

3.1.2. Drawbacks of Grid Connected System

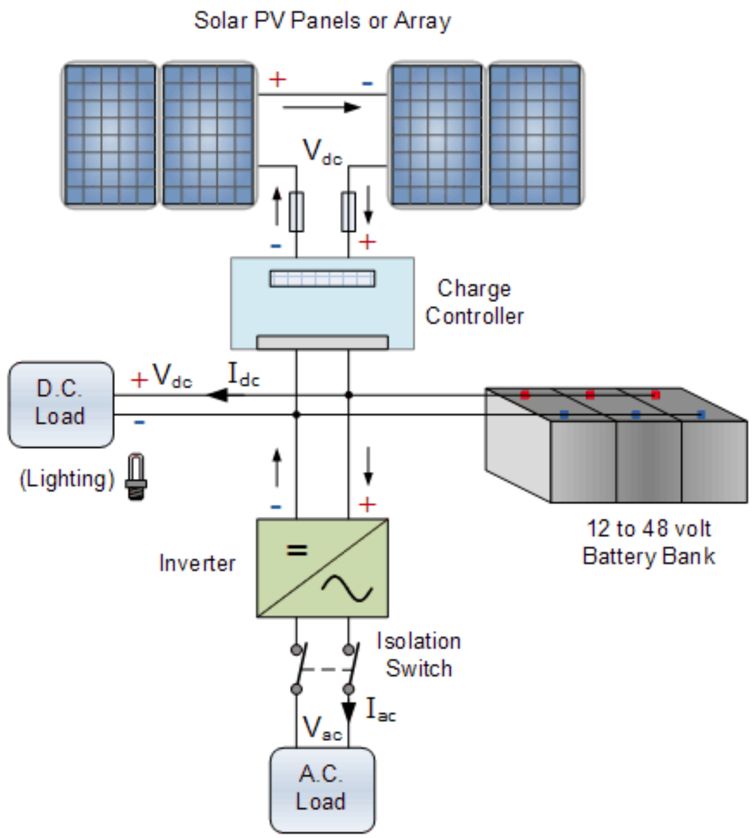
a. Does not prevent grid power failures
b. Can be dealt with by small battery bank

3.2 Standalone PV Systems

Off-grid PV systems have no connection to an electricity grid. A simple standalone PV system is an automatic solar system that produces electrical power to charge banks of batteries during the day for use at night when the suns energy is unavailable. Deep cycle lead acid batteries are generally used to store the solar power generated by the PV panels, and then discharge the power when energy is required. Deep cycle batteries are not only rechargeable, but they are designed to be repeatedly discharged almost all the way down to a very low charge.

A charge controller is connected in between the solar panels and the batteries. The charge controller operates automatically and ensures that the maximum output of the solar panels is directed to charge the batteries without over charging or damaging them.

An inverter is needed to convert the DC power generated into AC power for use in appliances.



Off-Grid PV System

Standalone PV systems are ideal for the electrification of rural areas or offshore sites that don't have utility grid service or where it would be very costly to have power lines run to the isolated buildings. In these cases, it is more cost effective to install a standalone PV system than pay the costs of having the local electricity company extend their power lines and cables directly to the home.

3.2.1. Benefits of Off-Grid Systems

a. System meets all electrical need for building

b. No connection to conventional power grid

c. Works in remote locations

d. Protection against power failures

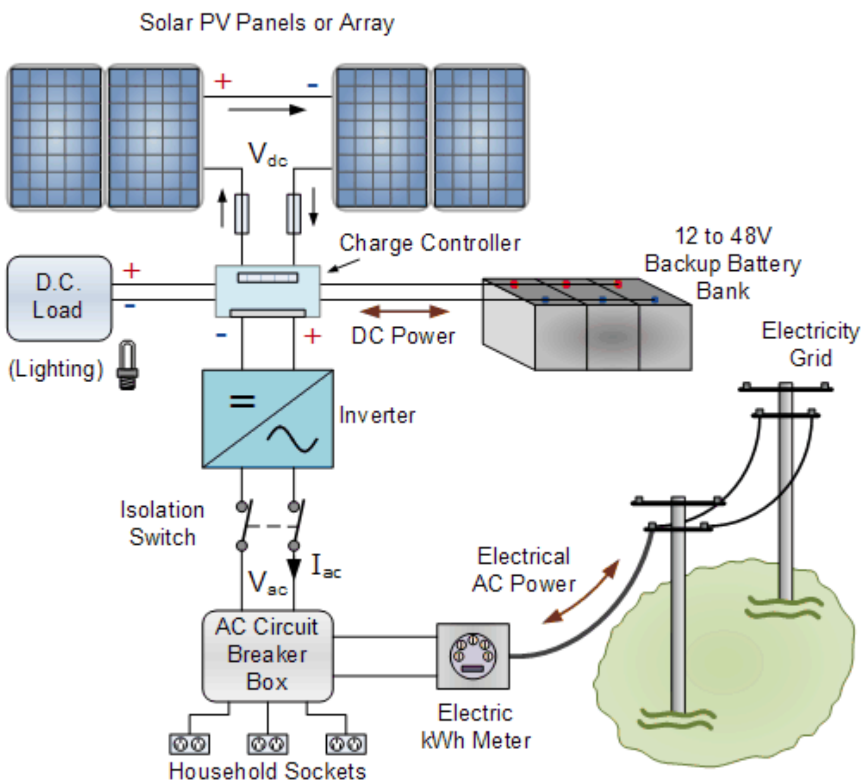
3.2.2. Drawbacks of Off-Grid Systems

a. Requires much more powerful system. It must produce more power than average consumption.

b. Significantly more expensive
c. Could run out of power

3.3 Grid Tied with Battery Backup System

Including a battery bank into the system allows utilization of energy produced from the PV system and stored in the batteries during a power out-age. A grid-tied PV system with battery backup is ideal when living in areas with unreliable power from the grid or that experience power outages due to natural disasters.



Grid Tied with Battery Backup

3.4 Comparison

The design of a PV system should consider whether the building should be able to operate wholly independent of the electrical grid, which requires batteries or other on-site energy storage systems. Here is the comparison.

Type	Stand Alone/ Off-Grid	Grid-Tied	Grid-Tied with Battery Backup
Complexity	Introduction of	Less components in	Introduction of

	Batteries and backup generator increases complexity	the system	Batteries and backup generator increases complexity. Requires different inverter.
Maintenance	Batteries increase maintenance need. More than Grid-Tied but less than Grid-Tied with battery back-up.	Less than the other systems.	Depending on batteries. More than other systems.
Life Span	Decreased due to batteries.	Longer than other systems due to decreased complexity.	Decreased due to batteries.
Energy/Economy	No utility bills. Increased cost of system.	Net metering allows financial gains from the energy utility if feed-in tariffs are possible.	Net metering allows financial gains from the energy utility if feed-in tariffs are possible. Increased cost of system.
Autonomy	Autonomous System. If power from PV modules cannot produce enough power, batteries and backup generator cover the critical loads.	Relies upon grid. If grid fails, the system shuts down and energy produced is wasted.	Larger autonomy. If grid fails, backup power from batteries is used to cover critical loads.

3.4.1. Recommendations

Is a Battery Bank Really Needed?

The simplest and least expensive configuration does not have battery back-up. Without batteries, a grid-connected PV system will shut down when a utility power outage occurs. Battery back-up maintains power to some or all the electric equipment, such as lighting, refrigeration, or fans, even when a utility power outage occurs. A grid-connected system may also have generator back-up if the facility cannot tolerate power outages.

With battery back-up, power outages may not even be noticed. However, adding batteries to a system comes with several disadvantages that must be weighed against the advantage of power back-up. These disadvantages are:

a. Batteries consume energy during charging and discharging, reducing the efficiency and output of the PV system by about 10 percent for lead-acid batteries.
b. Batteries increase the complexity of the system. Both first cost and installation costs are increased.
c. Lower cost batteries require more maintenance.
d. Batteries will usually need to be replaced before other parts of the system and at considerable expense.

CHAPTER - 4

INVERTERS

4.0. TYPES OF INVERTERS

Inverters which are also known as Power conditioning units, convert direct current (DC) electricity (from batteries or solar arrays) into alternating current (AC) electricity.

They may be classified into 3 types:

a. Stand-alone Inverters used in isolated systems not connected to the grid. The inverter draws its DC energy from batteries charged by photovoltaic arrays and supply AC energy to the facility use. Many stand-alone inverters also incorporate integral battery chargers to replenish the battery from an AC source, when available. Normally these do not interface in any way with the utility grid, and as such, are not required to have anti-islanding protection.
b. Grid Tie Inverters do not provide backup power during utility outages. They are designed to shut down automatically upon loss of grid supply, for safety reasons. They need to match phase with a utility-supplied sine wave.
c. Battery Backup Inverters: These are special inverters which are designed to draw energy from a battery, manage the battery charge via an onboard charger, and export excess energy to the utility grid. These inverters are capable of supplying AC energy to selected loads during a utility outage and are required to have anti-islanding protection.

When specifying an inverter, it is necessary to consider requirements of both the DC input and the AC output.

a. For a grid connected PV system, the DC input power rating of the inverter should be selected to match the PV panel or array.
b. For standalone systems, the power inverters are selected based on the input battery voltage, maximum load, the maximum surge required, variations in voltage and any optional features needed.

4.1 Standalone Inverters

Stand-alone inverters typically operate at 12, 24, 48- or 110-volts DC input and create 110- or 208-volts AC at 60 Hertz. The selection of the inverter input voltage is an important decision.

Let's understand some inverter terminology used in the manufacturers' datasheets:

4.1.1. Power Conversion Efficiency

This value gives the ratio of output power to input power of the inverter. Some power is lost in the conversion process. Modern inverters commonly used in PV power systems have peak efficiencies of 92-94%, but these again are measured under well-controlled factory conditions. Actual field conditions usually result in overall DC – to - AC conversion efficiencies of about 88-92%.

4.1.2. Duty Rating

This rating gives the amount of time the inverter can supply its rated power. Some inverters can operate at their rated power for only a short time without overheating. Exceeding this time may cause hardware failure.

4.1.3. Input Voltage

This is determined by the total power required by the AC loads and the voltage of any DC loads. Generally, the larger the load, the higher the inverter input voltage. This keeps the current at levels where switches and other components are readily available.

4.1.4. Surge Capacity

Most inverters can exceed their rated power for limited periods of time (seconds). Surge requirements of specific loads should be determined or measured. Some transformers and AC motors require starting currents several times their operating level for several seconds.

4.1.5. Standby Current

This is the amount of current (power) used by the inverter when no load is active (power loss). This is an important parameter if the inverter will be left on for long periods of time to supply small loads. The inverter efficiency is lowest when load demand is low.

4.1.6. Voltage Regulation

This indicates the variability in the output voltage. Better units will produce a nearly constant root-mean-square (RMS) output voltage for a wide range of loads.

4.1.7. Voltage Protection

The inverter can be damaged if DC input voltage levels are exceeded. Remember, battery voltage can far exceed nominal if the battery is overcharged. A 12-volt battery may reach 16 volts or more and this could damage some inverters. Many inverters have sensing circuits that will disconnect the unit from the battery if specified voltage limits are exceeded.

4.1.8. Frequency

Most loads in US require 60 Hz. High-quality equipment requires precise frequency regulation variations can cause poor performance of clocks and electronic timers.

4.1.9. Modularity

In some systems it is advantageous to use multiple inverters. These can be connected in parallel to service different loads. Manual load switching is sometimes provided to allow one inverter to meet critical loads in case of failure. This added redundancy increases system reliability.

4.1.10. Power Factor

The cosine of the angle between the current and voltage waveforms produced by the inverter is the power factor. For resistive loads, the power factor will be 1.0 but for inductive loads, the power factor will drop. Power factor is determined by the load, not the inverter.

4.2 Grid Connected Inverter

For grid-connection, the inverter must have the words “Utility-Interactive” printed directly on the listing label. Here are some guidelines:

4.2.1. Voltage Input

The inverter’s DC voltage input window must match the nominal voltage of the solar array, usually 235V to 600V for systems without batteries and 12, 24 or 48 volts for battery-based systems.

4.2.2. AC Power Output

Grid-connected systems are sized according to the power output of the PV array, rather than the load requirements of the building. This is because any power requirements above what a grid-connected PV system can provide is automatically drawn from the grid.

4.2.3. Surge Capacity

The starting surge of equipment such as motors is not a consideration in sizing grid-connected inverters. When starting, a motor may draw as much as seven times its rated wattage. For grid-connected systems, this start-up surge is automatically drawn from the grid.

4.2.4. Frequency and Voltage Regulation

Better quality inverters will produce near constant output voltage and frequency.

4.2.5. Efficiency

Modern inverters have peak efficiencies of 92 percent to 94 percent, as rated by their manufacturers. Actual field conditions usually result in overall efficiencies of about 88 percent to 92 percent. Inverters for battery-based systems have slightly lower efficiencies.

4.2.6. Maximum Power Point Tracking (MPPT)

Modern non-battery-based inverters include maximum power point tracking. MPPT automatically adjusts system voltage such that the PV array operates at its maximum power point. For battery-based systems, this feature has recently been incorporated into better charge controllers.

4.2.7. Inverter-Chargers

For battery-based systems, inverters are available with a factory-integrated charge controller, referred to as inverter-chargers. Be sure to select an inverter-charger that is rated for grid-connection, however. In the event of a grid power outage, use of an inverter-charger that is not set up for grid-connection would result in overcharging and damaging the batteries, known as "cooking the batteries."

4.2.8. Automatic Load Shedding

For battery-based systems, the inverter can automatically shed any unnecessary loads in the event of a utility power outage. Solar loads, i.e. the loads that will be kept powered up during the outage, are connected to a separate electrical sub-panel. A battery-based system must be designed to power these critical loads.

4.2.9. Disconnects

Automatic and manual safety disconnects protect the wiring and components from power surges and other equipment malfunctions. They also ensure the system can be safely shut down and system components can be removed for maintenance and repair. For grid-connected systems, safety disconnects ensure that the generating equipment is isolated from the grid, which is important for the safety of utility personnel. In general, a disconnect is needed for each source of power or energy storage device in the system.

For each of the functions listed below, it is not always necessary to provide a separate disconnect. For example, if an inverter is located outdoors, a single DC disconnect can serve the function of both the array DC disconnect and the inverter DC disconnect. Before omitting a separate disconnect, however, consider if this will ever result in an unsafe condition when performing maintenance on any component. Also consider the convenience of the disconnect' s location. An inconveniently located disconnect may lead to the tendency to leave the power on during maintenance, resulting in a safety hazard.

4.2.10. Array DC Disconnect

The array DC disconnect, also called the PV disconnect, is used to safely interrupt the flow of electricity from the PV array for maintenance or troubleshooting. The array DC disconnect may also have integrated circuit breakers or fuses to protect against power surges.

4.2.11. Inverter DC Disconnect

Along with the inverter AC disconnect, the inverter DC disconnect is used to safely disconnect the inverter from the rest of the system. In many cases, the inverter DC disconnect will also serve as the array DC disconnect.

4.2.12. Inverter AC Disconnect

The inverter AC disconnect disconnects the PV system from both the building's electrical wiring and the grid. Frequently, the AC disconnect is installed inside the building's main electrical panel. However, if the inverter is not located near the electrical panel, an additional AC disconnect should be installed near the inverter.

4.2.13. Exterior AC Disconnect

Utilities commonly require an exterior AC disconnect that is lockable, has visible blades and is mounted next to the utility meter so that it is accessible to utility personnel. An AC disconnect located inside the electrical panel or integral to the inverter would not satisfy these requirements. One alternative that is as acceptable to some utilities as an accessible AC disconnect is the removal of the meter itself, but this is not the norm. Prior to purchasing equipment, consult the electric utility to determine their requirements for interconnection.

4.2.14. Battery DC Disconnect

In a battery-based system, the battery DC disconnect is used to safely disconnect the battery bank from the rest of the system.

4.3 Installation

An inverter should be installed in a controlled environment because high temperatures and excessive dust will reduce lifetime and may cause failure. The inverter should not be installed in the same enclosure with the batteries because the corrosive gassing of the batteries can damage the electronics and the switching in the inverter might cause an explosion. However, the inverter should be installed near the batteries to keep resistive losses in the wires to a minimum. After conversion to AC power, the wire size can be reduced because the AC voltage is usually higher than the DC voltage. This means the AC current is lower than the DC current for an equivalent power load.

CHAPTER - 5

CHARGE CONTROLLERS

5.0. CHARGE CONTROLLER

A charge controller, sometimes referred to as a photovoltaic controller or battery charger, is only necessary in standalone systems with battery back-up.

The primary function of a charge controller is to prevent overcharging of the batteries or limiting excessive discharge. Overcharging can boil the electrolyte from the battery and cause failure. Allowing the battery to be discharged too much will cause premature battery failure and possible damage to the load. The controller is a critical component in the PV system. A controller's function is to control the system depending on the battery "State-of-charge" (SOC). When the battery nears full SOC the controller redirects or switches off all or part of the array current. When the battery is discharged below a preset level, some or the entire load is disconnected if the controller includes the low voltage disconnect (LVD) capability. Most controllers use a measurement of battery voltage to estimate the state-of-charge. Measuring battery temperature improves the SOC estimate and many controllers have a temperature probe for this purpose.

Some modern charge controllers incorporate maximum power point tracking (MPPT), which optimizes the PV array's output, increasing the energy it produces. The major principle of MPPT is to extract the maximum available power from the PV module or array, by making them operate at the most efficient voltage (maximum power point). This voltage is matched to the battery voltage, in order to insure maximum charge (amps). The PV module or string of modules maximum power point defines the current that should be drawn from the PV in order to get the most possible power (power is equal to voltage times current).

5.1 Charge Regulation

There are two main charging regulation methods:

a. Interrupting (on/off) regulation. The controller leads all available PV current to the battery during charging. On reaching the maximum allowable voltage, the controller switches off the charging current. When the voltage falls to VR – VRH, the current is reconnected.

b. Constant voltage regulation. The controller can modify the VR set-point by sensing the battery condition or using a low VR in order to avoid excessive gassing, coupled with provision for an occasional gassing ‘equalization’ charge.

5.2 Types of Charge Controllers

There are essentially two types of controllers: shunt and series.

5.2.1. Shunt Controller

The shunt (parallel) regulator has a switch that is open when the battery is charging and closes when the battery is fully charged. These controllers require a large heat sink to dissipate the excess current.

5.2.2. Series Controller

Series controllers disconnect the array when the battery voltage reaches the high voltage level. These are small and inexpensive and have a greater load-handling capacity than shunt-type controllers. These can be single PMW, single stage or multistage types

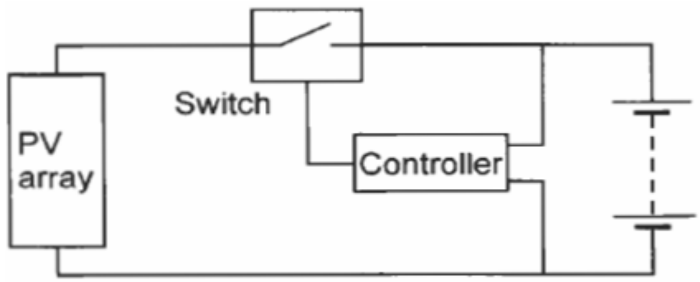
PMW controllers

Some controllers regulate the flow of energy to the battery by switching the current fully on or fully off. This is called "on/off control." Others reduce the current gradually. This is called "pulse width modulation" (PWM). Both methods work well when set properly for your type of battery. A PWM controller holds the voltage more constant. If it has two-stage regulation, it will first hold the voltage to a safe maximum for the battery to reach full charge. Then, it will drop the voltage lower, to sustain a "finish" or "trickle" charge. Two-stage regulating is important for a system that may experience many days or weeks of excess energy (or little use of energy). It maintains a full charge but minimizes water loss and stress.

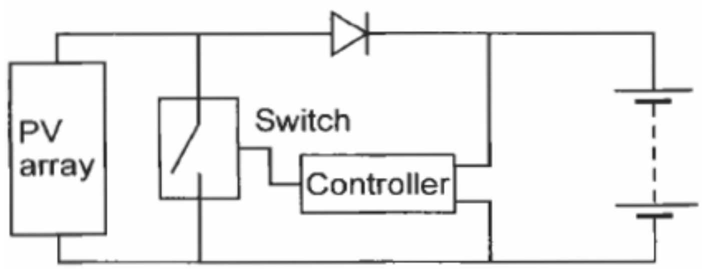
Multistage controllers

Multistage controllers allow different charging currents as the battery nears full state-of charge. This technique also provides a more efficient method of charging the battery. As the battery nears its full state of charge (SOC) - its internal resistance increases and using lower charging current wastes less energy.

Most charge controllers are three-stage controllers. These chargers have dramatically improved battery life.



Series Controller



Shunt Controller

The voltages at which the controller changes the charge rate are called set points. When determining the ideal set points, there is some compromise between charging quickly before the sun goes down, and mildly overcharging the battery. The determination of set points depends on the anticipated patterns of usage, the type of battery, and to some extent, the experience and philosophy of the system designer or operator. Some controllers have adjustable set points, while others do not.

5.3 Selection of Charge Controllers

Charge controllers are selected based on:

a. PV array voltage – The controller's DC voltage input must match the nominal voltage of the solar array.
b. PV array current – The controller must be sized to handle the maximum current produced by the PV array. The total current from PV array is calculated by the number

of modules or strings in parallel, multiplied by the module current. It is better to use the short-circuit current (I_{SC}) instead of the maximum power current (I_{MP}) so that the shunt type controllers which operate the array at short-circuit current conditions are safe. The peak array current ratings for charge controllers should be sized for about 125% safety margin.

c. Interaction with Inverter – Since most charge controllers are used in off-grid systems, their default settings may not be appropriate for a grid-connected system. The charge controller must be set up such that it does not interfere with the proper operation of the inverter. In particular, the controller must be set up such that charging the batteries from the PV array takes precedence over charging from the grid. For more information, contact the manufacturer.

d. Interaction with Batteries – The charge controller must be selected to deliver the charging current appropriate for the type of batteries used in the system. Most PV systems use deep-cycle lead-acid batteries of either the flooded type or the sealed type. Sealed batteries need to be regulated to a slightly lower voltage than flooded batteries or they will dry out and be ruined. For example, on a 12V system, flooded lead-acid batteries have a voltage of 14.6V to 15.0V when fully charged, while sealed lead-acid batteries are fully charged at 14.1 V. Refer to the battery manufacturer for the charging requirements of batteries. Never use a controller that is not intended for your type of battery.

e. Temperature compensation - The ideal set points for charge control vary with a battery's temperature. Some controllers have a feature called "temperature compensation." When the controller senses a low battery temperature, it will raise the set points. Otherwise when the battery is cold, it will reduce the charge too soon. If the batteries are exposed to temperature swings greater than about 17°C, compensation is essential.

CHAPTER - 6

BATTERIES

6.0. BATTERIES

Batteries accumulate excess energy created by the PV system and store it to be used at night or when there is no other energy input. Since a photovoltaic system ‘s power output varies throughout any given day, the battery storage system can provide a relatively constant power source, even when the photovoltaic system is disconnected for repair and maintenance or producing minimal power in periods of reduced sunlight.

Battery Bank

In general, electrical storage batteries can be divided into two major categories, primary and secondary batteries.

a. Primary Batteries- Primary batteries can store and deliver electrical energy but cannot be recharged. Typical carbon-zinc and lithium batteries commonly used in consumer electronic devices are primary batteries. Primary batteries are not used in PV systems because they cannot be recharged.

b. Secondary Batteries- A secondary battery can store and deliver electrical energy and can also be recharged by passing a current through it in an opposite direction to the discharge current. Rechargeable batteries are the most effective storage mechanism available.

Battery storage capacity is rated in ampere hours, which is the current delivered by the battery over a set number of hours, at a normal voltage, and at a temperature of 25ºC. Most PV systems use lead acid batteries or conventional flooded batteries. Nickel cadmium batteries are usually the best option when very high reliability is required.

6.1 Batteries Types and Classification

Types of batteries commonly used in PV systems are:

a. Lead-acid batteries
   - Flooded (a.k.a. Liquid vented)
   - Sealed (a.k.a. Valve-Regulated Lead Acid)
     - Absorbent glass mat
     - Gel cell

b. Alkaline batteries
   - Nickel-cadmium
   - Nickel-iron

6.2 Lead Acid Batteries

Lead-acid batteries are most common in PV systems, as they are cheap, reliable and have relatively good energy storage density. Lead battery cells consist of two lead plates immersed in dilute sulphuric acid which creates a voltage of about 2V between the plates. Cells are then connected in series to have 12V batteries. These are available as flooded and sealed configurations.

a. Flooded lead-acid batteries are the most common lead-acid batteries. They contain vents which allow the resulting hydrogen gas from electrolysis escape. As a result, the electrolyte level will fall over a period of time, and must be monitored and topped up with water, preferably distilled water. The hydrogen gas produced is highly flammable. Care must be taken to ensure that there is adequate ventilation above and around flooded batteries.

b. Sealed batteries are spill proof and do not require periodic maintenance. Also known as Valve regulated lead acid (VRLA) batteries these contain electrolyte, which is immobilized in some manner. Under excessive overcharge, the normally sealed vents open under gas pressure through a pressure regulating mechanism. Electrolyte cannot be replenished in these battery designs; therefore, they are intolerant of excessive overcharge. VRLA batteries are available in two different technologies: Absorbed Glass Mat (AGM) and Gelled Electrolyte. AGM lead-acid batteries have become the industry standard, as they are maintenance free and particularly suited for grid-tied systems where batteries are typically kept at a full state of charge. Gel-cell batteries, designed for freeze-resistance, are generally a poor choice because any overcharging will permanently damage the battery.

The following describe the types of Lead-acid batteries commonly used in PV systems;

6.2.1. Lead-Antimony Batteries

Lead-antimony batteries are a type of lead-acid battery which uses antimony (Sb) as the primary alloying element with lead in the plate grids. The use of lead-antimony alloys in the grids has both advantages and disadvantages.

Advantages include providing greater mechanical strength than pure lead grids, and excellent deep discharge and high discharge rate performance. Lead- antimony grids also limit the shedding of active material and have better lifetime than lead- calcium batteries when operated at higher temperatures.

Disadvantages of lead-antimony batteries are a high self-discharge rate, and as the result of necessary overcharge, require frequent water additions depending on the temperature and amount of overcharge. Most lead-antimony batteries are flooded, open vent types with removable caps to permit water additions. They are well suited to application in PV systems due to their deep cycle capability and ability to take abuse, however they do require periodic water additions. The frequency of water additions can be minimized by the use of catalytic recombination caps or battery designs with excess electrolyte reservoirs. The health of flooded, open vent lead- antimony batteries can be easily checked by measuring the specific gravity of the electrolyte with a hydrometer. Lead-antimony batteries with thick plates and robust design are generally classified as motive power or traction type batteries, are widely available and are typically used in electrically operated vehicles where deep cycle long-life performance is required.

6.2.2. Lead-Calcium Batteries

Lead-calcium batteries are a type of lead-acid battery which uses calcium (Ca) as the primary alloying element with lead in the plate grids. Like lead-antimony, the use of lead-calcium alloys in the grids has both advantages and disadvantages. Advantages include providing greater mechanical strength than pure lead grids, a low self-discharge rate, and reduced gassing resulting in lower water loss and lower maintenance requirements than for lead-antimony batteries. Disadvantages of lead-calcium batteries include poor charge acceptance after deep discharges and shortened battery life at higher operating temperatures and if discharged to greater than 25% depth of discharge repeatedly.

a. **Flooded Lead-Calcium, Open Vent**- Often classified as stationary batteries, these batteries are typically supplied as individual 2-volt cells in capacity ranges up to and over 1000 ampere-hours. Flooded lead-calcium batteries have the advantages of low self-discharge and low water loss and may last as long as 20 years in stand-by or float service. In PV applications, these batteries usually experience short lifetimes due to sulfation and stratification of the electrolyte unless they are charged properly.

b. **Flooded Lead-Calcium, Sealed Vent**- Primarily developed as 'maintenance free' automotive starting batteries, the capacity for these batteries is typically in the range of 50 to 120 ampere-hours, in a nominal 12-volt unit. Like all lead-calcium designs, they are intolerant of overcharging, high operating temperatures and deep discharge cycles. They are “maintenance free” in the sense that you do not add water, but they are also limited by the fact that you cannot add water which generally limits their useful life. This battery design incorporates sufficient reserve electrolyte to operate over its typical service life without water additions. These batteries are often employed in small stand-alone PV systems such as in rural homes and lighting systems but must be carefully charged to achieve maximum performance and life. While they are low cost, they are really designed for shallow cycling, and will generally have a short life in most PV applications.

6.2.3. Lead-Antimony/Lead-Calcium Hybrid

These are typically flooded batteries, with capacity ratings of over 200 ampere-hours. A common design for this battery type uses lead-calcium tubular positive electrodes and pasted lead- antimony negative plates. This design combines the advantages of both lead-calcium and lead- antimony design, including good deep cycle performance, low water loss and long life.

6.3 Alkaline Batteries

Because of their relatively high cost, alkaline batteries are only recommended where extremely cold temperatures (-50°F or less) are anticipated or for certain commercial or industrial applications requiring their advantages over lead-acid batteries. These advantages include tolerance of freezing or high temperatures, low maintenance requirements, and the ability to be fully discharged or over-charged without harm.

The most common type of alkaline battery used for PV system is Nickel Cadmium battery.

6.3.1. Nickel Cadmium Batteries

Nickel-cadmium (NiCd) batteries are secondary or rechargeable batteries and have several advantages over lead-acid batteries that make them attractive for use in stand-alone PV systems. These advantages include long life, low maintenance, and survivability from excessive discharges, excellent low temperature capacity retention, and non-critical voltage regulation requirements. The main disadvantages of nickel-cadmium batteries are their high cost and limited availability compared to lead-acid designs. A typical nickel-cadmium cell consists of positive electrodes made from nickel-hydroxide ($NiOH_2$) and negative electrodes made from cadmium (Cd) and immersed in an alkaline potassium hydroxide (KOH) electrolyte solution. When a nickel- cadmium cell is discharged, the nickel hydroxide changes form ($NiOH_2$) and the cadmium becomes cadmium hydroxide ($CdOH_2$). The concentration of the electrolyte does not change during the reaction, so the freezing point stays very low.

NiCd batteries can be completely discharged without damage and the electrolyte will not freeze. NiCd batteries are more expensive but can withstand harsh weather conditions. Because nickel cadmium batteries can be discharged nearly 100 percent without damage, some designers do not use a controller, if NiCd batteries are used.

6.4 Battery Parameters

Deep cycle batteries are generally used in solar PV systems and are especially designed for the type of charging and discharging cycles they need to endure. These batteries can be characterized (in addition to their ability to be recharged) by high power density, high discharge rate, flat discharge curves, and good low-temperature performance.

The most common type of batteries used in solar PV applications are maintenance free "lead acid batteries" as this type of battery is the most cost effective for energy storage. Parameters associated with deep cycle lead acid batteries are:

6.4.1. Battery Voltage

Voltage is electrical pressure. A standard car battery is 12 volts. This voltage is the addition of the six (6) smaller lead acid cells connected in series which make up a larger 12V battery. Each individual lead acid cell has a voltage of about 2 volts. Battery banks used for alternative energy systems are usually connected in series to produce DC voltages of 12, 24, 36, or 48 volts.

6.4.2. Battery Current

Current is the flow of electrons. The rate of this flow per unit time is called an ampere. Batteries store power as direct current (DC) which is used for lighting or to power the inverter which changes it into alternating current (AC). The maximum deliverable current from deep cycle batteries is the highest current a battery can drive through a load without its terminal voltage dropping significantly due to the battery's internal resistance, and without causing the battery to overheat. Deep cycle batteries are connected in parallel to increase the available output current.

6.4.3. Rated Battery Capacity

Battery capacity is the amount of energy a battery contains and is usually rated in Ampere-hours (Ah) at a given voltage. So, a battery with a rating of 1,000 ampere-hours can deliver 100 amperes for 10 hours, or 10 amperes for 100 hours, or 1 ampere for 1000 hours and so on. To determine the total amount of power a deep cycle battery can deliver, multiply the ampere-hours (Ah) by the terminal voltage. The storage capacity of an average car battery is about 40 to 85 ampere-hours.

You will not be able to obtain rated capacity repeatedly when the batteries are used in PV systems. However, rated capacity sets a baseline on which to compare-battery performance. **Important:** When comparing the rated capacity of different batteries, be sure the same discharge rate is being used.

6.4.4. Depth of Discharge (DOD)

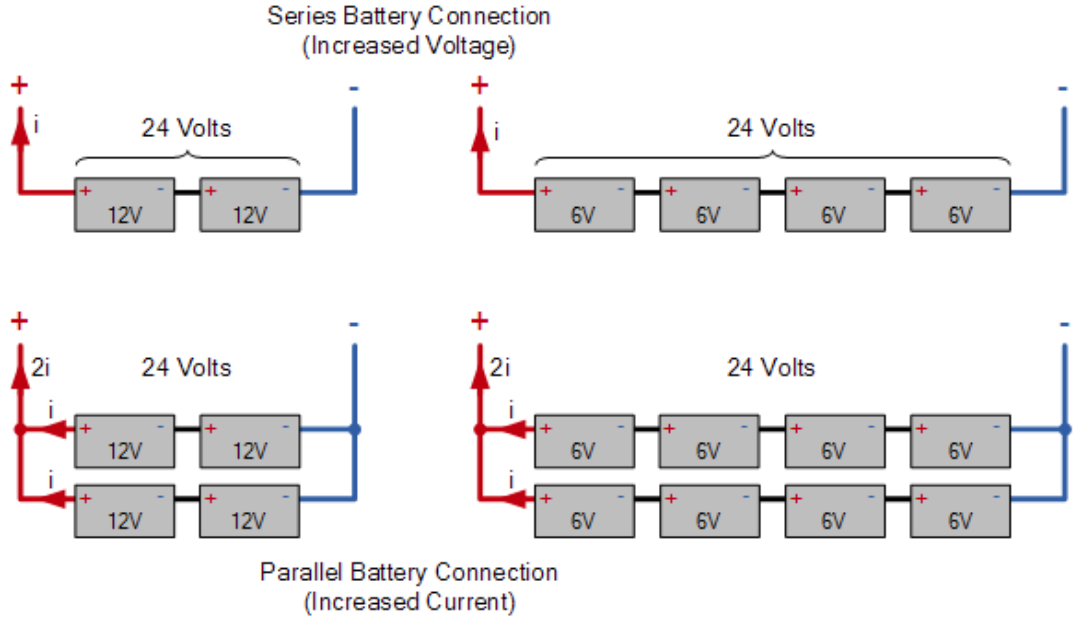
Depth of Discharge (DOD) is the percentage of the rated battery capacity that is withdrawn from the battery. The capability of a battery to withstand discharge depends on its construction. Two terms, shallow-cycle and deep-cycle are commonly used to describe batteries.

a. **Shallow Cycle batteries** are lighter, less expensive, and will have a shorter lifetime particularly if recommended discharge levels are exceeded regularly. Many sealed (advertised as no maintenance) batteries are shallow-cycle types. Generally, the shallow-cycle batteries should not be discharged more than 25 percent.
b. **Deep Cycle batteries** are designed to be repeatedly charged and discharged all the way down to a very low charge, by as much as 80% of their full capacity (100% to 20% state of charge) without sustaining any serious damage to the cells.

Deep cycle batteries are designed specifically for storing the energy and then discharging this for use on a consistent, daily basis. Unlike a regular car battery, the physical size of a deep cycle battery is much larger due to the construction and size of the lead plates (electrodes). These plates are made of solid lead usually doped with Antimony (Sb) and are many times thicker than the thinner sponge type plates of a car battery. This means then that deep cycle batteries can be repeatedly discharged almost all the way down to a very low charge and it is not uncommon for deep cycle batteries to be emptied (discharged) to as much as 20% of their total capacity before energy ceases flowing from the battery.

6.4.5. Deep Cycle Battery Wiring

Figure below shows an example of connecting batteries together of different voltages, such as 6 volt and 12-volt batteries, to produce a 24 volt battery bank. Any number of batteries can be connected in series to produce an output voltage that is a multiple of the battery voltage. In our example this is 2 x 12 volts = 24 volts. Likewise, batteries connected in parallel increases the current by the number of branches. However, it is better to limit the number of connect branches to a maximum of three (3) as parallel battery banks tend to circulate unwanted currents from branch to branch.



6.4.6. Temperature Correction

Batteries are sensitive to temperature extremes and a cold battery will not provide as much power as a warm one. Most manufacturers provide temperature correction charts to correct for temperature effects. For instance, a battery at 25°C has 100 percent capacity, if discharged at a current rate of C/20. (The discharge rate is given as a ratio of the rated capacity, C, of the battery.) However, a battery operating at 0°C would have only 75 percent of the rated capacity if discharged at a C/20 rate. If the discharge rate is higher, say C/5, only 50 percent of the rated capacity will be available when the temperature is minus 20°C.

At higher temperatures, a battery will deliver more than its specified capacity by the manufacturer, but the rate of discharge is increased, and thus the battery' life is shortened. Battery should be kept near room temperature close to 25°C.

Batteries should be located in an insulated or other temperature-regulated enclosure to minimize battery temperature variations. This enclosure should be separated from controls or other PV system components for safety reasons. Adequate ventilation of these enclosures is required, for the removal of toxic and explosive mixtures of gasses (hydrogen) that may be produced by the batteries.

6.4.7. State-of-Charge (SOC)

This is the amount of capacity remaining in a battery at any point in time. It is equal to 1 minus the depth of discharge given as a percentage.

6.4.8. Battery Life (cycles)

The lifetime of any battery is difficult to predict because it depends on several factors such as charge and discharge rates, depth of discharges, number of cycles, and operating temperatures. It would be unusual for a lead acid type battery to last longer than 15 years in a PV system but many last for 5-10 years. Nickel cadmium batteries will generally last longer when operated under similar conditions and may operate satisfactorily for more than 15 years under optimum conditions.

6.4.9. Charging Cycle

The ideal charging cycle of a battery includes the following stages:

a. The battery is charged at constant current until the voltage reaches a predefined value.
b. The voltage is held constant while the charging current decays.
c. After suitable time the charging voltage is reduced to avoid excessive gassing and loss of electrolyte.

Caution: The ideal charging cannot be achieved to a PV system, where the available power is constantly changing.

In stand-alone systems, the cycle of the battery is within 24 hours, charging during daytime and discharging at night. Typical daily discharge may range from 2 -20% of the battery capacity.

6.4.10. Days of Autonomy

Autonomy refers to the number of days a battery system will provide a given load without being recharged by the photovoltaic array. Correctly selecting a number of days will depend on the system, its location, its total load and the nature of the system’s load.

Weather conditions determine the number of no sun days which may be the most significant variable in determining autonomy.

6.4.11. Potential Problems

When designing the PV system potential problems such as sulphation, stratification and freezing should be considered and avoided.

a. **Sulphation** occurs when the battery is discharged and if the voltage falls below the discharge cut-out voltage (deep discharge), and the acid concentration undergoes a strong reduction.

b. **Stratification** occurs when acid forms layers of different density on cycling. Batteries that are regularly deep discharged and then fully recharged, concentrate lower density acid at the bottom; while batteries with regular shallow cycling which are not 100% recharged concentrate lower density acid at the top.

c. **Freezing** in lead-acid battery occurs as the battery is discharged; the acid becomes more 'watery' and the freezing point is raised which can cause severe problems if the battery is operating in sub-zero temperatures.

Very good lead acid batteries may work for up to 4.500 cycles at 30% depth of discharge (DOD) which is equivalent to 20 years lifetime.

6.4.12. Interaction with Solar Modules

The solar array must have a higher voltage than the battery bank in order to fully charge the batteries. For systems with battery back-up, pay attention to the rated voltage of the module, also called the maximum power point (V_{MP}) in the electrical specifications. It is important that the voltage is high enough relative to the voltage of a fully charged battery. For example, rated voltages between 16.5V and 17.5V are typical for a 12V system using liquid lead-acid batteries. Higher voltages may be required for long wiring distances between the modules and the charge controller and battery bank.

6.5 Battery Rating and Sizing

The nominal capacity of the battery is given from the following equation:

$Q_n = I_n \times T_n$

- I_n: constant discharge current, amp

- T_n: discharge time, h

The battery has to store energy for many days and used without going over the DOD $_{max}$.

The following equation can be used:

$$Q = \frac{E \times A}{V \times T \times \eta_{Inv} \times \eta_{cable}}$$

- Q = minimum battery capacity required, Ah
- E = daily energy requirement, Wh
- A = number of days of storage required
- V = system DC voltage, V
- T = maximum allowed DOD of the battery usually on battery data sheet (indicatively 0.3 -0.9)
- ηinv = inverter efficiency (1,0 if there's no inverter)
- ηcable = efficiency of the cables delivering the power from battery to loads.

6.5.1. Battery Installation

Batteries should be installed in an enclosed space, separated from controls or other PV system components which may have cooling/heating mechanisms in order to protect them from excessive temperatures. When temperature swings are reduced, battery will have a better performance, longer life, and lower maintenance.

6.5.2. Battery Maintenance

Batteries require periodic maintenance. For flooded batteries, the electrolyte level should be maintained well above the plates and the voltage and specific gravity of the cells should be checked for consistent values. The specific gravity of the cells should be checked with a hydrometer particularly before the onset of winter. In cold environments, the electrolyte in lead-acid batteries may freeze. The freezing temperature is a function of a battery state of charge. When a battery is completely discharged, the electrolyte becomes water and the battery may freeze.

Even the sealed battery should be checked to make sure connections are tight and there is no indication of overcharging.

6.5.3. Battery Safety

Batteries which are used in photovoltaic systems are potentially dangerous if improperly handled, installed, or maintained. Dangerous chemicals, heavy weight and high voltages and currents are potential hazards and can result in electric shock, burns explosion or corrosive damage to your person or property.

Also, hydrogen gasses and fumes emitted during charging of these lead acid deep cycle batteries are irritant and potentially explosive, so always ventilate the battery area well. Clean any spillages of electrolyte on or around the batteries and check the battery terminals and cables for tightness lubricating with petroleum jelly if needed. With proper care and maintenance, deep cycle lead acid batteries will have a long service life in any solar powered PV system.

Gloves, eye protection such as goggles and masks must be worn when handling lead acid batteries and electrolyte as “battery acid” both burns and irritates skin and eyes.

6.6 Selection of Battery for PV Systems

Some of the considerations made when sizing the battery are:

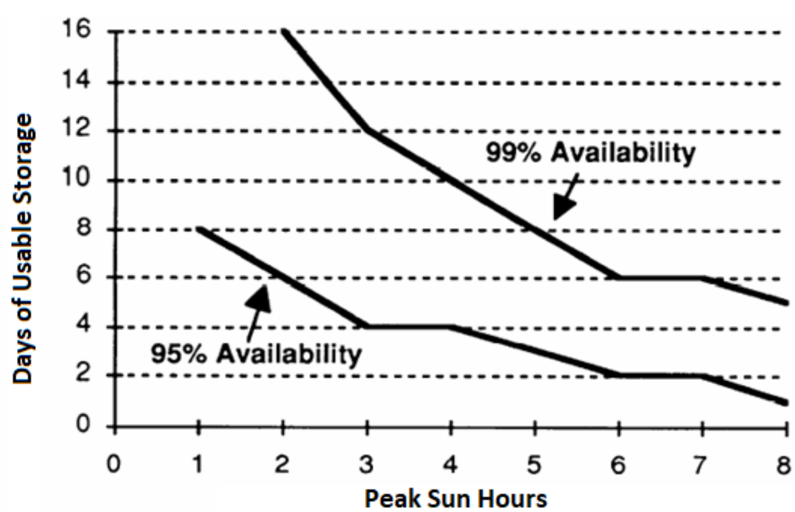
a. First, the amount of back-up energy to be stored is calculated. This is usually expressed as a number of cloudy days the system will operate using energy stored in batteries. This depends on the type of service, the type of battery, and the system availability desired. Areas with extended periods of cloudiness would need more storage capacity to keep the load going during these periods of inclement weather. Also, if it is critical that loads always have power, it is advisable to have a more storage or large battery capacity.
b. The difference between rated battery capacity and usable capacity should be understood. Many Battery manufacturers publish the “rated battery capacity” (the amount of energy that their battery will provide, if discharged once under favorable conditions of temperature and discharge rate). This is usually much higher than the

amount of energy that can be taken out of the battery repeatedly in a PV application. For example:

- Shallow-cycle, sealed batteries will have the usable capacity of only 20 percent of the rated capacity, i.e., taking more than 20 ampere-hours from a 100-ampere-hour battery will cause the battery to quickly fail.
- Deep cycling batteries will have usable capacities up to 80 percent of rated capacity.

For most PV applications the bigger and heavier the battery, the better it is.

c. Also, there are many types of batteries with a large variance in quality and cost. Figure below gives a starting point for making battery size selection using the design month peak sun hours. Just find the peak sun hours for the design month and read up to the days of storage for system availabilities of 95 or 99 percent. It is important to buy quality batteries that can be discharged and recharged many times before failure. *Automobile batteries should not be used as these are designed to produce a high current for a short time. The battery is then quickly recharged. PV batteries may be discharged slowly over many hours and may not be recharged fully for several days or weeks.*



d. Finally, it is important to understand the close interrelation between the battery and the charge controller. When a battery is bought a compatible charge controller should be purchased.

CHAPTER - 7

BALANCE OF SYSTEM

7.0. AUXILIARY ITEMS

These components provide the interconnections and standard safety features required for any electrical power system. These include array combiner box, properly sized cabling, fuses, switches, circuit breakers and meters.

7.1 Distribution Board – AC Breaker & Inverter AC Disconnect Panel

A component of the electricity supply system, where all the electrical wiring of the house meets with the provider of the electricity, whether that's the grid or a solar-electric system. It divides the electrical power feed into subsidiary circuits for various rooms in the house, while providing a protective fuse or circuit breaker for each circuit, protecting the building's wiring against electrical fires and safeguarding the circuit's electrical wiring. These breakers also allow electricity to be disconnected for servicing.

7.1.1. Battery Over current Protection

The output conductors of the battery bank shall be protected against over current, by high rupturing capacity (HRC) fuses or DC rated circuit breakers, as follows:

a. Where the battery bank is electrically floating (i.e. neither side of the battery is earthed), protection shall be provided in both positive and negative battery leads.

b. Where one side of the battery bank is earthed, protection shall be provided in the unearthed battery lead.

7.1.2. Disconnection Devices

Safety disconnects or switches are placed into power systems to allow equipment to be safely installed and maintained. Typically, there are four locations where disconnect devices are needed in photovoltaic systems. They are:

a. Between the array and the charge regulator

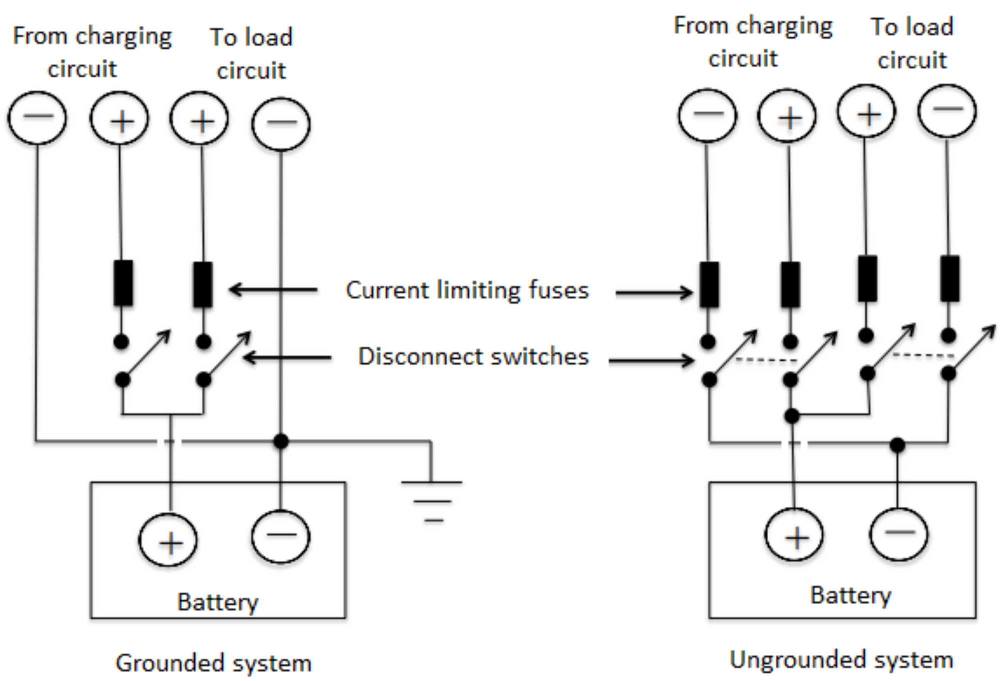
b. Between the regulator and the battery

c. Between the battery and any DC loads or load center

d. Between the battery and the inverter.

In many cases the disconnection means can be combined with the over-current protection in the form of a DC circuit breaker. If this is done, care needs to be taken to ensure that the circuit breaker chosen is fit for purpose; for example, polarized DC circuit breakers cannot be used in many situations.

The location of fault current protection related to battery systems is generally between the battery and charge controller. The protection should be mounted as close as practicable to the battery terminals while offering no possibility for spark ignition of any hydrogen emitted from the batteries during charging.



Battery Overcurrent and Disconnect Requirement

7.2 Meters and Instrumentation

Essentially two types of meters are used in PV systems:

a. Utility Kilowatt-hour Meter
b. System Meter

7.2.1. Utility Kilowatt-Hour Meter

A meter that measures electricity exported to the grid (when the energy generation is exceeding the needs) or imported from the grid (when the energy generation does not meet the energy demands). Switch from import to export and vise verse takes place automatically without any human intervention.

7.2.2. System Meter

System meters measure and display the charge of the battery bank, production of electricity from solar panels and amount of electricity in use. It is possible to operate a system without a system meter, though meters are strongly recommended. Modern charge controllers incorporate system monitoring functions and so a separate system meter may not be necessary.

7.3 Combiner Box

Wires from individual PV modules or strings are run to the combiner box. These wires may be single conductor pigtails with connectors that are pre-wired onto the PV modules. The output of the combiner box is one larger two-wire conductor in conduit. A combiner box typically includes a safety fuse or breaker for each string and may include a surge protector.

7.4 Surge Protection

Surge protectors help to protect your system from power surges that may occur if the PV system or nearby power lines are struck by lightning. A power surge is an increase in voltage significantly above the design voltage.

7.5 Earthing & Grounding

Earthing is the procedure where one or more parts of an electrical system are physically connected to ground, which is considered to have zero volt potential. Whereas in "Grounding" the circuit is not physically connected to ground, but its potential is zero with respect to other points. The key differences are:

Earthing	Grounding
This method protects the human being from	This method protects the entire power system

electrocuted.	from malfunctioning.
Earthing contains zero potential.	Grounding does not possess any zero potential.
The earth wire used is green in colour.	The wire used for grounding is black in colour
Earthing is primarily used to avoid shocking the humans.	Grounding is primarily used for unbalancing when the electric system overloads.
Earthing is located under the earth pit, between the equipment body underground.	It is located between the neutral of the equipment being used and the ground.

All components of PV system and any exposed metal, including equipment boxes, receptacles, appliance frames and PV mounting equipment should connect to a grounding electrode (the metallic device used to make actual contact with earth). An equipment-grounding conductor is a conductor that does not normally carry current and is connected to earth.

Earthing is an important safety requirement to prevent electrical shocks caused by a ground fault. A ground fault occurs when a current-carrying conductor comes into contact with the frame or chassis of an appliance or electrical box.

7.6 Cables & Wiring

Important considerations on cables & wiring:

a. Array cables should be suitable for DC application, water resistant and UV-resistant.
b. Reinforced or double-insulated cables should be used when laid in metallic tray or conduit.
c. Total voltage drop in all AC and DC cables shall be less than 4%.
d. Cables are to be laid/ installed in such a way that all connections and wiring should be protected from inadvertent contact and mechanical damage.
e. Cable shall have ability to carry current safely without overheating in specified conditions that cable will be laid/ installed.

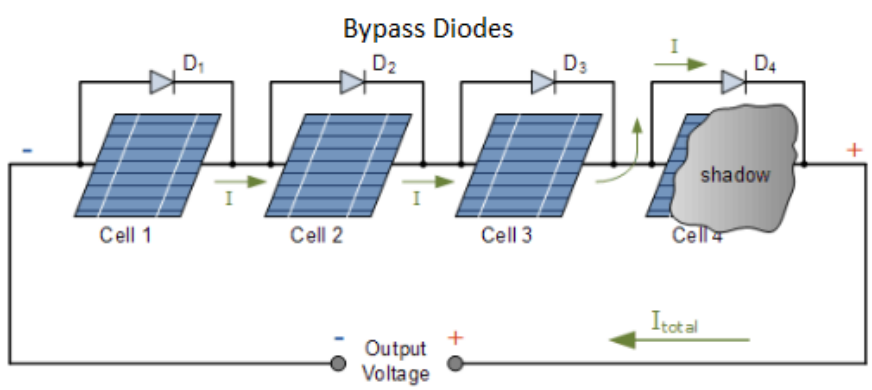
f. String fuses can be used to protect cables from overloading and are usually used for systems with more than four strings. The permitted current rating of the cable should be at least equal or greater than the trigger current of the string fuse.

g. Three crucial parameters must be considered when sizing the cables:

- cable voltage ratings
- current rating of the cable
- minimizing of cable losses

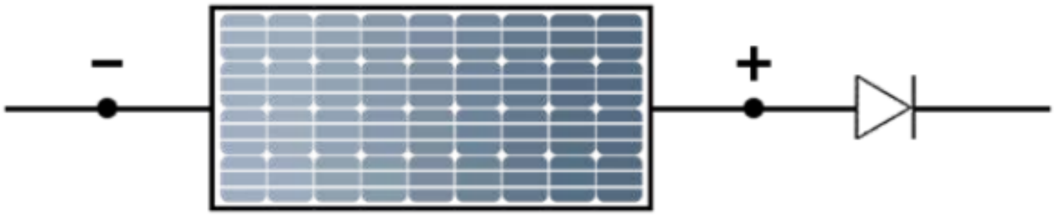
7.6.1. Bypass Diodes

When a cell in photovoltaic module is damaged or a part of module is shaded, the shaded cells will not be able to produce as much current as the un-shaded cells. Since all the cells are connected in series, the same amount of current will flow through the damaged or shaded cell that will now act as a resistance and become hot and energy generated in the module will be lost. This is known as 'hotspot' phenomenon. This can be avoided by using a bypass diode in the module in parallel to the output terminal as shown in the diagram below.



7.6.2. Blocking Diodes

During daylight, an array has more voltage potential than the battery, so current flows from the array into the battery. But at night, the module potential drops to zero, and the battery could discharge all night backwards through the module. This would not be harmful to the module but would result in loss of precious energy from the battery bank. Diodes placed in the circuit between the module and the battery can block any nighttime leakage flow.



Blocking Diode

CHAPTER - 8

DESIGN AND SIZING OF PV SYSTEM

8.0. DESIGN & SIZING PRINCIPLES

Appropriate system design and component sizing is fundamental requirement for reliable operation, better performance, safety and longevity of solar PV system.

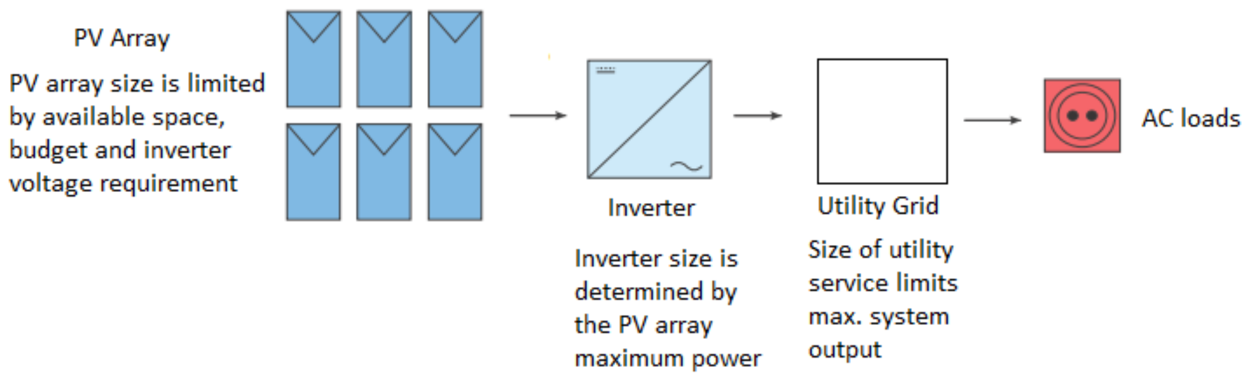
The sizing principles for grid connected and stand-alone PV systems are based on different design and functional requirements.

a. Grid Connected Systems (without energy storage)
    - Provide supplemental power to facility loads.
    - Failure of PV system does not result in loss of loads.
b. Stand-Alone Systems (with energy storage)
    - Designed to meet a specific electrical load requirement.
    - Failure of PV system results in loss of load.

8.1 System Sizing for Grid Connected Systems

The sizing for grid connected systems without energy storage generally involves the following:

a. Determining the maximum array power output.
b. Based on the available area, efficiency of PV modules used, array layout and budget.
c. Selecting one or more inverters with a combined rated power output 80% to 90% of the array maximum power rating at STC.
d. Inverter string sizing determines the specific number of series-connected modules permitted in each source circuit to meet voltage requirements.
e. The inverter power rating limits the total number of parallel source circuits.
f. Estimating system energy production based on the local solar resource and weather data.
g. The sizing of interactive PV systems is centered on the inverter requirements.



Grid connected PV System

8.2 Sizing for Grid Tie Solar System

The following steps will help you determine the array size for your grid tie solar photovoltaic system.

8.2.1. Find you monthly average electricity usage from your energy bill

This is the total kWh you pay for in a single month. Due to seasonal usage like air conditioning, space heating, it is recommended to look at bills from several months of the year. Using all the data available, determine your monthly average electricity usage.

8.2.2. Find your daily average electricity usage

Divide your monthly average kWh found in step 1 by 30 days.

8.2.3. Find the daily average peak sun hours for your location

If you can't find your location or you need more information regarding the data source, please visit: https://maps.nrel.gov/pvdaq. Refer Annexure -2 at the end of this course.

8.2.4. Calculate the solar system size (AC) to generate 100% of your electricity consumption

Divide you daily average energy usage (step 2) by the average sun peak hours in your location. For example, if your average energy usage is 34 kWh/Day and you live in New Orleans (4.5 Peak Sun Hours) your solar system size (AC) should be: 34kWh / 4.5 h = 7.55 kW. Multiply by 1000 to get Watts.

NOTE: The solar system size calculated in step 4 is in Alternative Current (AC), which is the output of a solar system. The solar modules constitute the input of your solar system; therefore, we need to include the system inefficiencies in order to estimate the number of solar panels you need. A common grid-tie solar system will lose about 14-22% during energy conversion, these accounts for cabling, inverter, connections, etc.

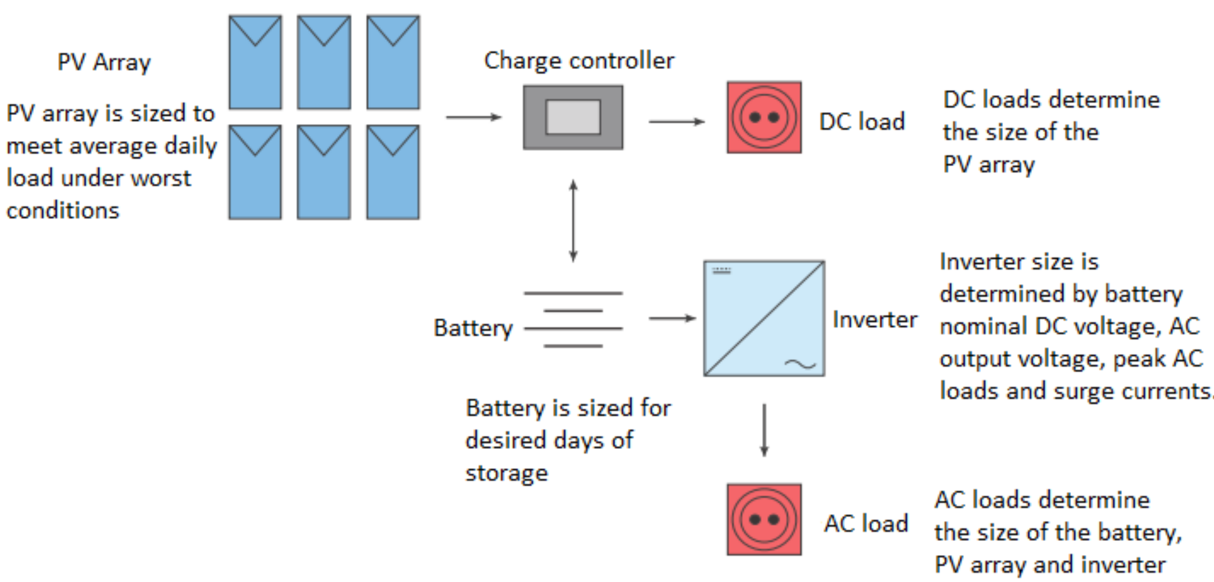
8.2.5. Calculate the number of solar panels needed for this system

Considering a well-designed solar system with 86% efficiency (14% loss), divide the solar system size (AC) in step 4 by 0.86. It looks like: 7.55 kW / 0.86 = 8.78 kW.

Let's say you want to use a solar module with a nominal name plate power of 220 Watt. In that case you will need: 8.78 kW x 1000 / 220 W = 39.90 panels. Always round this number up. In this case, you will require 40 solar modules at 220 Watt each to cover 100% of your energy needs.

8.3 Sizing Your Standalone Systems

Standalone or off-grid PV systems are different from grid-connected inverters. Stand-alone PV systems can be considered a type of banking system. The battery is the bank account. The PV array produces energy (income) and charges the battery (deposits), and the electrical loads consume energy (withdrawals).



Standalone PV System with Battery and Inverter

The sizing objective for stand-alone PV system is a critical balance between energy supply and demand. It involves the following key steps:

a. Determine the average daily load requirements for each month.

b. Conduct a critical design analysis to determine the month with the highest load to solar insolation ratio.
c. Size battery bank for system voltage and required energy storage capacity.
d. Size PV array to meet average daily load requirements during period with lowest sunlight and highest load (usually winter).
e. Sizing stand-alone PV systems begins with determining the electrical load, and then sizing the battery and PV array to meet the average daily load during the critical design month.

Let's discuss the selection of different components of Standalone system in detail.

8.4 System Sizing

Sizing a photovoltaic system for a stand-alone photovoltaic power system involves a five-step process which will allow the photovoltaic system designer or user to accurately size a system based on users projected needs, goals and budget. These steps are:

a. Estimating the Electric Load
b. Sizing and Specifying an Inverter
c. Sizing and Specifying Batteries
d. Sizing and Specifying an Array
e. Specifying A Controller

8.4.1. Estimating the Electric Load

The first task for any PV system design is to determine the system load. The load determination is straightforward. Make a list of the electrical appliances and/or loads to be powered by the PV system. The power required by an appliance can be measured or obtained from the label on the back of appliance which lists the wattage. You can also refer a typical power consumption demand of common devices at the end of the course (Annexure-1). Once you have the wattage ratings, fill out the load sizing worksheet (refer below). The power requirements are calculated by multiplying the number of hours per day that specific appliances will operate each day.

For existing buildings, other alternative is to get consumption figures from your utility invoice; it shows actual usage over a 12-month period.

Electrical Characteristics

A1	Inverter efficiency	0.85 to 0.9%
A2	Battery Bus voltage	12V, 24V or 48V
A3	Inverter AC voltage	120 V or 408V for USA (60 Hz frequency)

Important Steps for Load Analysis

The load is determined by listing all appliances with their power ratings and operation hours then summing it to obtain the total average energy demand in watt-hours or kilowatt-hours. Worksheet below gives ideas of how to estimate the load.

It is good to list both the AC and DC loads separately because sizing of inverter is required for AC demands only. Apply inverter efficiency to determine the DC energy required for AC loads.

Adjust for DC and AC loads by applying adjustment factor. This will give the 'Adjusted Watts'. The 'Average Daily Load' is then computed by multiplying the Adjusted Watts by the hours of use per day.

Electric Load Compilation (Sample Worksheet)

	A4	**A5**	**A6**	**A7**	**A8**
Appliances	Rated Wattage **(Watts)**	Adjustment Factor **1.0 for DC** **A1 for AC**	Adjusted Wattage **(A4/A5)**	Hours per day used **(hrs)**	Energy per day **(A6xA7)**
-----	-----	-----	-----	-----	-----
-----	-----	-----	-----	-----	-----
-----	-----	-----	-----	-----	-----

Electric Load Estimation

A9	Total energy demand per day **(sum of A8)**	-----	watt-hours
A10	Total amp-hour demand per day **(A9/A2)**	-----	amp-hours
A11	Maximum AC power requirement **(sum of A4)**	-----	watts
A12	Maximum DC power requirement **(sum of A6)**	-----	watts

Calculation and Explanation

	Parameters	**Values**	**Explanation**
A1	Inverter efficiency	0.85 - 0.9	This quantity is used as a power adjustment factor when current is changed from DC to AC.
A2	Battery Bus voltage	12V, 24V or 48V	Battery bus voltage corresponds to the required DC input voltage for the inverter. Follow below for guidance. Use 12V up to 1kWh Use 24V from 1 kWh to 3 to 4 kWh Use 48 V exceeding 4 kWh
A3	Inverter AC voltage	120 V or 408V for US (60 Hz frequency)	The output voltage of the inverter is designed for single-phase 120V or three phase 408V at 60Hz frequency.
A4	Rated Wattage	Watts	The rated wattage is listed for each appliance in column (A4).
A5	Adjustment Factor	1.0 for DC 0.85 for AC	The adjustment factor is related to the efficiency of the inverter. The efficiency of the inverter varies anywhere between 0.85 - 0.9. For DC loads operating straight from the battery bank an adjustment factor of 1.0 is used.
A6	Adjusted Wattage	$\frac{A4}{A5}$	Dividing the rated wattage (A4) by the adjustment factor (A5) adjusts the wattage to compensate for the inverter inefficiency and gives the actual wattage consumed from the battery bank.
A7	Hours per day Used	hrs	The number of hours each appliance is used per day. The duty cycle, or actual time of load operation, must be considered here.
A8	Energy per day	A6xA7	The amount of energy each appliance requires

			per day is determined by multiplying each appliance's adjusted wattage (A6) by the number of hours used per day (A7).
A9	Total energy demand per day	Sum of A8	The Sum of the Quantities in column (A8) determines the total energy demand required by the appliances per day. It is calculated in watt-hours.
A10	Total amp-hour demand per day	$\frac{A9}{A2}$	The battery storage is sized independently of the photovoltaic array. In order to size the battery bank the total electrical load is converted from watt-hours to amp-hours.
A11	Maximum AC power requirement	Sum of A4	This value is the maximum continuous AC power output required of the inverter, if all loads were to operate simultaneously. This does not include surge requirements. The Peak, or surge requirement (due to motor starting, etc.) must also be considered when selecting an inverter.
A12	Maximum DC power requirement	Sum of A6	This value (A12) is the maximum DC input power required by the inverter and is necessary to determine wire sizes fusing and disconnect requirement. If load management techniques are employed to eliminate the possibility of loads operating simultaneously, the inverter maximum output requirements may be reduced accordingly.

8.5 Battery Sizing

Batteries for stand-alone systems are sized to store energy produced by the array for use by the system loads as required. The total amount of rated battery capacity required depends on the following:

a. Desired days of storage to meet system loads with no recharge from PV

b. Maximum allowable depth-of-discharge

c. Temperature and discharge rates

d. System losses and efficiencies

e. The system voltage defines the number of series-connected battery cells required.

f. The total capacity needed defines the number of parallel battery strings required.

8.5.1. Days of Storage or Autonomy

a. Autonomy is the number of days that a fully charged battery can meet the system loads without any recharge from the PV array.

b. Greater autonomy periods are used for more critical applications and increase system availability, but at higher cost due to the larger battery required.

Important: Batteries should be capable of meeting both the power and energy requirements of the system. As a rule of thumb, the minimum autonomy should be kept as 3 days for regular loads. For critical loads autonomy should be more than 3 days based on weather conditions of the particular area.

8.5.2. Factors Affecting Battery Sizing

a. The specified autonomy and maximum allowable depth of discharge (DOD) defines the total amount of battery capacity required for a given system load.

b. Greater autonomy periods increase the size of the battery and increase availability and decrease average daily depth-of- discharge.

c. Greater allowable DOD provides greater system availability, but at the expense of battery health.

d. Rated battery capacity is affected by temperature, discharge rate and age of the battery.

Sizing the battery bank for the worst case is not only important for ensure that the PV system can cover the loads of the building under all conditions, but also because to increase the chances of minimizing the seasonal battery depth of discharge. In addition, you should also consider your usage pattern and the criticality of your application.

8.5.3. Sample Worksheet for Battery Sizing

Item	Parameters	Values	Explanation
B1	Days of storage desired/required (autonomy)	days	Normally, the battery storage system is designed to provide the necessary electrical energy for a period equivalent to 7 days without any sunshine. This time period is considered a moderate level of

Item	Parameters	Values	Explanation
			storage. Less critical applications may use 3 to 4 days of storage, although this would increase the depth of the battery cycling and reduce battery life. For critical applications such as those that would impact public safety, more days of storage may be desirable.
B2	Allowable depth-of-discharge limit (decimal)	0.8	This is the maximum fraction of capacity that can be withdrawn from the battery. Note that the battery selected must be capable of this limit or greater depth of discharge. Typical value is 0.8 for a good new battery.
B3	Required battery capacity (amp – hours)	$\frac{(\mathrm{A10 \ x \ B1})}{\mathrm{B2}}$	The required battery capacity is determined by first multiplying the total amp-hours per day (A10) by the days of storage required (B1) and then dividing this number by the allowable depth of discharge limit (B2).
B4	Amp-Hour capacity of selected battery [Note -1]	Refer Note -1 below	Once the required number of amp-hours has been determined (B3), batteries or battery cells can be selected using manufacturers' information. Refer Note -1 below.
B5	Number of batteries in parallel	$\frac{\mathrm{B3}}{\mathrm{B4}}$	Parallel connection attains higher capacity by adding up the total ampere-hour (Ah).
B6	Number of batteries in series	A2 / selected battery voltage	Batteries achieve the desired system voltage (operating voltage) by connecting several cells in series; each cell adds its voltage potential to derive at the total terminal voltage.
B7	Total Number of Batteries	B5xB6	Multiplying the number of batteries in parallel (B5) by the number of battery cells in series (B6).
B8	Total battery amp-hour capacity (amp-hours)	B5xB4	The total rated capacity of selected batteries is determined by multiplying the number of batteries in parallel (B5) by the ampere-hour (Ah) capacity of the selected battery (B4).

Note -1 (Refer Item B4):

Once the required number of amp-hours has been determined (B3), batteries or battery cells can be selected using manufacturers' information. Figure below shows the extract of industrial grade battery for different day rates. Since battery capacity may vary with the rate of discharge, the amp-hour capacity that corresponds to the required days of storage should be used.

			20 DAY (480 HR)		10 DAY (240 HR)		5 DAY (120 HR)		3 DAY (72 HR)		
TYPE	VOLTS PER UNIT	NORMAL A.H. CAP	A.H	AMPS	A.H	AMPS	A.H	AMPS	A.H	AMPS	32° F (0° C) 500 HR A.H.
6E95-5	12	180	192	0.40	192	0.80	192	1.60	192	2.67	184
6E95-7	12	270	288	0.60	288	1.20	288	2.40	288	4.00	276
6E95-9	12	360	383	0.80	383	1.60	383	3.19	383	5.32	368
6E95-11	12	450	478	1.00	478	1.99	478	3.98	478	6.64	459
6E120-9	12	500	538	1.12	538	2.24	538	4.48	538	7.47	516
6E120-11	12	625	673	1.40	673	2.80	673	5.61	673	9.35	646
6E120-13	12	750	808	1.68	808	3.37	808	6.73	808	11.22	776
6E120-15	12	875	942	1.96	942	3.93	942	7.85	942	13.08	904
3E120-17	6	1000	1077	2.24	1077	4.49	1077	8.98	1077	14.96	1034
3E120-19	6	1125	1212	2.53	1212	5.05	1212	10.10	1212	16.83	1163
3E120-21	6	1250	1346	2.80	1346	5.61	1346	11.22	1346	18.69	1292
3E120-23	6	1375	1481	3.09	1481	6.17	1481	12.34	1481	20.57	1422
3E120-25	6	1500	1616	3.37	1616	6.73	1616	13.47	1616	22.44	1551
3E120-27	6	1625	1750	3.65	1750	7.20	1750	14.58	1750	24.31	1680
3E120-29	6	1750	1885	3.93	1885	7.85	1885	15.71	1885	26.18	1809

8.6 PV Array Sizing

Solar array size is determined by the following parameters:

a. The PV array for stand-alone systems is sized to meet the average daily load during the critical design month.

b. Solar insolation received in the site

c. System losses, soiling and higher operating temperatures are factored in estimating array output.

d. Characteristics of the PV modules

e. The system voltage determines the number of series-connected modules required per source circuit.

f. The system power and energy requirements determine the total number of parallel source circuits required.

The array is sized to meet the average daily load requirements for the month or season of the year with the lowest ratio daily insolation to the daily load. Using module power output and daily insolation (in peak sun hours), the energy (watt- hours or amp-hours) delivered by a photovoltaic module for an average day can be determined. Then, knowing the requirements of the load and the output of a single module, the array can be sized. Higher system availability can be achieved by increasing the size of the PV array and/or battery.

8.6.1. Sample Worksheet for PV Array

Item	**Parameters**	Values	**Explanation**
C1	Total energy demand per day (watt-hours)	A9	Total energy demand per day in watts – hour.
C2	Battery round trip efficiency	0.70 and 0.85	A factor between 0.70 and 0.85 is used to estimate battery round trip efficiency. Use 0.85, if the battery selected is relatively efficient and if a significant percentage of the energy is used during daylight hours.
C3	Required array output per day (watt-hours)	$\frac{C1}{C2}$	Dividing the total energy demand per day (C1) by the battery round trip efficiency (C2) determines the required array output per day. The watt-hours required by the load are adjusted (upwards) because batteries are less than 100% efficient.
C4	Selected PV module max power voltage at STC (Volts)	P_{max} x.85	Selected PV module max power voltage at STC x 0.85. Maximum power voltage is obtained from the manufacturer's specifications for the selected photovoltaic module, and this quantity is multiplied by 0.85 to establish a design operating voltage for each module (not the array).
C5	Selected PV module guaranteed power output at STC (watts)	Manufacturer's datasheet	Selected PV module guaranteed power output (in watts) at STC. This number is also obtained from

			the manufacturer's specifications for the selected module.
C6	Peek sum hours at design tilt for design month	hours	Peak sun hours at optimum tilt. This figure is obtained from solar radiation data for the design location and array tilt for an average day during the worst month of the year. (Refer annexure 2 at the end)
C7	Energy output per module per day (watt-hours)	C5xC6	The amount of energy produced by the array per day during the worst month is determined by multiplying the selected photovoltaic power output at STC (C5) by the peak sun hours at design tilt.
C8	Module energy output at operating temperature (watt-hours)	DF x C7	Multiplying the de-rating factor (DF) by the energy output module (C7) establishes an average energy output from one module. DF = 0.80 for hot climates and critical applications. DF = 0.90 for moderate climates and non-critical applications.
C9	Number of modules required to meet energy requirements (modules)	$\frac{C3}{C8}$	Dividing the required output per day (C3) by the module energy output at operating temperature (C8) determines the number of modules required to meet energy requirements.
C10	Number of modules required per string rounded to the next higher integer.	$\frac{A2}{C4}$	Dividing the battery bus voltage (A2) by the module design operating voltage (C4), and then rounding this figure to the next higher integer determines the number of modules required per string.
C11	Number of strings in parallel rounded to the next higher integer.	$\frac{C9}{C10}$	Dividing the number of modules required to meet energy requirements (C9) by the number of modules required per string (C10) and then rounding this

			figure to the next higher integer determines the number of string in parallel.
C12	Number of modules to be purchased	C10 x C11	Multiplying the number of modules required per string (C10) by the number of strings in parallel (C11) determines the number of modules to be purchased.
C13	Nominal rated PV module output (watts)	Manufacturer data	The rated module output in watts as stated by the manufacturer. Photovoltaic modules are usually priced in terms of the rated module output ($/watt).
C14	Nominal rated array output (watts)	C12 x C13	Multiplying the number of modules to be purchased (C12) by the nominal rated module output (C13) determines the nominal rated array output. This number will be used to determine the cost of the photovoltaic array.

Note: The design method for the PV array often uses current (amperes) instead of power (watts) to describe the load requirement because it is easier to make a meaningful comparison of PV module performance. For example, it is far convenient to compare performance, physical size and cost when specifying PV modules that will produce 30 amperes at 12 volts @ specified operating temperature rather than try to compare 50-watt modules that may have different operating points.

8.7 Selecting an Inverter

Inverter is required to convert direct current to alternating current. Stand-alone inverters are typically voltage-specific, i.e. the inverter must have the same nominal voltage as your battery. The inverter is rated in Watts. The input rating of the inverter should never be lower than the total watt of the appliances i.e.

Inverter Capacity $\geq$ A12 Watts

Important: The size of an inverter for standalone system is measured by its maximum continuous output in watts and this rating must be larger than the total wattage of all the connected AC loads. Also, electrical appliances such as washing machines, dries, refrigerators, etc. use electric motors, which require more power to start. This high starting power consumption can be more than twice the normal power consumption so the input rating of the inverter should be ideally 25-30% bigger than the rated wattage of your appliances.

8.8 Sizing the Controller

The function of a charge controller is to regulate the charge going into your batteries bank from your solar panel array and prevent overcharging and reverse current flow at the night. Most used charge controllers are Pulse width modulation (PWM) or Maximum power point tracking (MPPT).

The voltage at which PV module can produce maximum power is called maximum power point (or peak power voltage). Maximum power varies with solar radiation, ambient temperature and solar cell temperature. Typical PV module produces power with maximum power voltage of around 17V when measured at a cell temperature of 25°C, it can drop to around 15V on a very hot day and it can also rise to 18V on a very cold day. When a MPPT solar charge controller notices variations in current-voltage characteristics of solar cell, it will automatically and efficiently correct the voltage. it forces PV module to operate at voltage close to maximum power point to draw maximum available power.

MPPT solar charge controller allows users to use PV module with a higher voltage output than operating voltage of battery system. For example, if PV module has to be placed far away from charge controller and battery, its wire size must be very large to reduce voltage drop. With a MPPT solar charge controller, users can wire PV module for 24 or 48 V (depending on charge controller and PV modules) and bring power into 12 or 24 V battery system. This means it reduces the wire size needed while retaining full output of PV module.

The charge controller current input rating is equal to the product of the short circuit current of the PV module, number of PV modules in parallel, and safety factor, where safety factor 1.25.

$I_{Rated} = (N_{PV\text{-}parallel} \times I_{sc}) \times 1.25$

Where:

- I_{Rated} = Solar charge controller rating
- I_{sc} =Short circuit current
- $N_{B\text{-}parallel}$ = Number of PV modules in parallel
- 1.25 is safety factor

8.9 Cable Sizing

The purpose of this step is to estimate the size and the type of wire in the following loops:

a. Cable between PV modules and Batteries
b. Cable between the Battery Bank and the Inverter
c. Cable between the Inverter and Load

The equation below can be used to determine the cross section of copper wire.

$$A = \frac{p \times L \times I \times 2}{V_d}$$

Where:

- p=resistivity of wire ----- [For copper $p=1.724 \times 10^{-8}\ \Omega \cdot m$]
- L = length of wire (in m)
- A = cross sectional area of cable in mm^2
- I =the rated current of regulator, amps
- V_d =Voltage drop, volts

In both AC and DC wiring, the voltage drop is taken not to exceed 4 % value.

$$V_d = \frac{4}{100} \times V$$

The voltage V is typically,

a. Cable between PV modules and Batteries = 12V, 24 V or 48V
b. Cable between the Battery Bank and the Inverter = 12V, 24V or 48V
c. Cable between the Inverter and Load = 110 V

Please refer to an example, showing the step involved in sizing of Standalone PV components in Annexure-3 at the end of the course.

CHAPTER - 9

BUILDING INTEGRATED PHOTOVOLTAIC SYSTEMS

9.0. BIPV SYSTEMS

Building Integrated Photovoltaic (BIPV) is an application where solar PV modules are integrated into the building structures. The integration could be made by either installing the PV modules on top of existing structures or by blending the PV modules as part of the building elements (facades, roofs, walls, glass), and as non-building elements (sunscreen, sunshade). Modern commercial building facades often cost as much as a PV façade which means immediate or short-term payback for the PV system. Depending on the type of integration, the PV modules may also provide shading or noise protection.

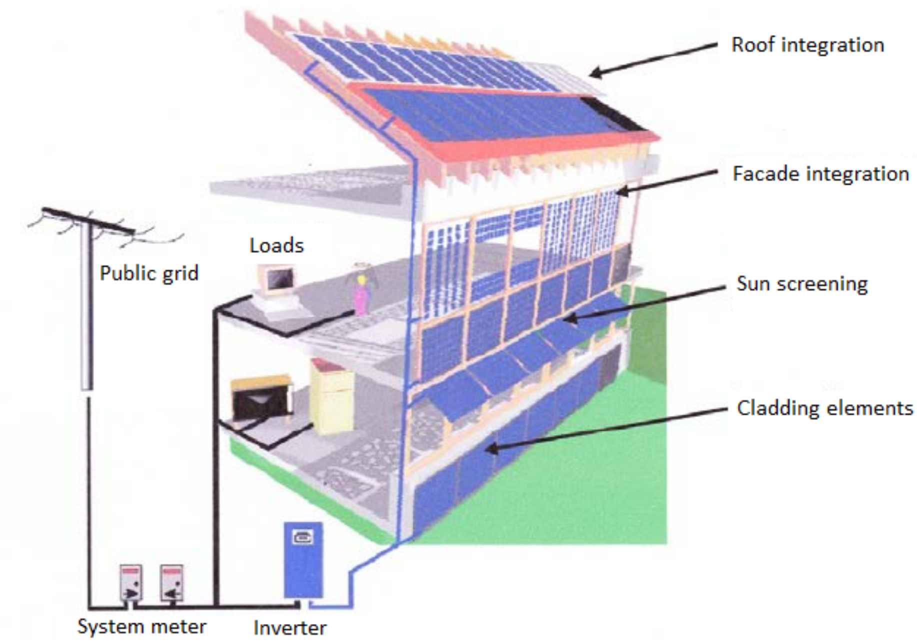
9.1 Benefits of BIPV

Building-integrated photovoltaic's can be used for different functions, such as:

a. **Replacing conventional materials:** One of the key benefits of using BIPV is the replacement of traditional building materials like roof membrane, facade cladding or skylight glazing, etc. BIPV modules can be fully customized in size, color, shape and so on. Therefore, it is the ultimate element for an architect to include in the building and it can be fully part of the characteristics of the structure.
b. **Cost reduction:** The major advantage of BIPV over the regular solar systems is that the initial cost can be offset by reducing money spent on construction materials and labor that would normally be used to construct the part of the building that the BIPV panels replace. Not only are they lower in cost but also have less environmental impact.
c. **Power generation:** Building-integrated photovoltaic components can generate sufficient power for a building or can export to a utility company thorough a grid interconnection. There are different technologies and projects that work in conjunction with these to ensure a rich energy harvest.
d. **Creation of shade:** Modules can protect against the weather, unwanted solar heat as well as protection from wind and rain. They also protect against lightning, being an electrical resistor.

e. **Thermal insulator:** When the weather gets cold (or hot), non-ventilated BIPV modules act as thermal insulation through the sandwich construction of the modules.

f. **Architectural integration:** They can provide comparatively more aesthetic appeal than conventional materials. For instance: using photovoltaic's cells for skylight systems in entrance halls, atria or courtyards, can be both economical with the use of solar energy and at the same time it serves as an exciting design feature.



Typical BIPV Elements

9.2 Architectural Criteria for BIPV

A successful BIPV solution requires interaction between building design and PV system design.

The dimensions of the PV system should match the dimensions of the building. This will determine the dimensions of the modules and the building grid lines used. Remember, that it is independent of the output capacity of the PV system.

The criteria for good integration of PV modules in buildings are:

1. Aesthetically pleasing composition of materials and colors
2. Applied seamlessly
3. Well contextualized in line with the context of the building

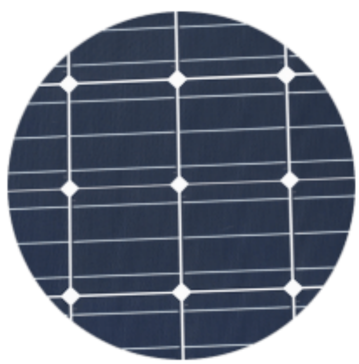
9.2.1. Aesthetically Pleasing

PV system must add eye-catching features to the design.

The building should look attractive and the PV system should noticeably improve the design.

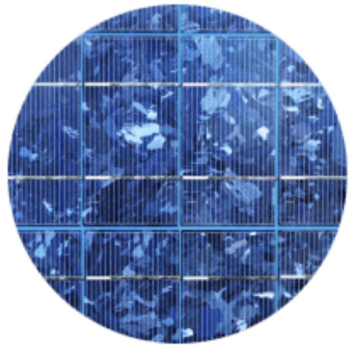
The color and texture of the PV system should be in harmony with the other materials. PV cells usually have a dark color as they are designed to reflect as few light as possible. This way the solar cell will produce maximum power output.

Monocrystalline modules – Monocrystalline solar cells are typically dark blue, black or grey. These panels have a high-power output, occupy less space, and last the longest. Of course, that also means they are the most expensive of the bunch. Another advantage to consider is that they tend to be slightly less affected by high temperatures compared to polycrystalline panels. The silicon's high purity causes this type of solar panel has one of the highest efficiency rates, with the newest ones reaching above 20%.



Monocrystalline

Polycrystalline modules – Polycrystalline solar cells are usually bluish speckled tone. They are made by melting raw silicon, which is a faster and cheaper process than that used for monocrystalline panels. This leads to a lower final price but also lower efficiency (around 15%), lower space efficiency, and a shorter lifespan since they are affected by hot temperatures to a greater degree.



Polycrystalline

Amorphous silicon (A-Si) - Thin-film amorphous silicon modules are a reddish-brown to black as common colors; the surface may appear uniform or non-uniform, depending on how the modules are made. Amorphous silicon (A-Si) cells are long and very narrow and thus appear more as a striated pattern from the outside; from the inside the appearance is like a half-open louver. The color of the light transmitted will depend on the colors absorbed by the cell on the way through. They are also flexible—which opens a lot of opportunities for alternative applications—and is less affected by high temperatures. The main issue is that they take up a lot of space.

Thin film Solar Cells

The color of the solar cells can be changed by varying the thickness of the anti-reflection coating. Some PV manufacturers can fill special orders for colors such as gold, green, and magenta. These color variations will result in some loss in performance efficiencies.

The colored cells give a special look to the solar installation, however by adjusting the thickness of the anti-reflection layer, the overall reflection will increase, and the efficiency will decrease by 15-30% depending on the color.

PV panel with different colored cells

9.2.2. Well Contextualized

The total image of the building should be in harmony with the PV system. It is important to introduce texture without overshadowing the modules. Texture is the feel or shape of a surface or substance; the smoothness, roughness, softness, etc.

Strategies for introducing texture includes: using stippled glass effects at the module edges; alternating PV modules with other materials; using a light-box detail; using stainless steel laminate clips; combining a variety of PV technology types; combining a variety of differently specified modules; forward mounting the modules so they cast a shadow on the supporting wall; tilting to allow highlights to be produced; providing non-uniform spacing between cells; exploiting the PV as a homogeneous material to form symbolic shapes. Acid etching of the module's front side glass is sometimes used to reduce reflection in the overall façade and to provide contrast between the PV cladding and the windows.

It requires architects with vision, in combination with a solar expert that knows the available products and applications very well. For example, on a historic building, tiles or slates will probably fit better than large glass modules. A high-tech PV system, however, would fit better in a high-tech building.

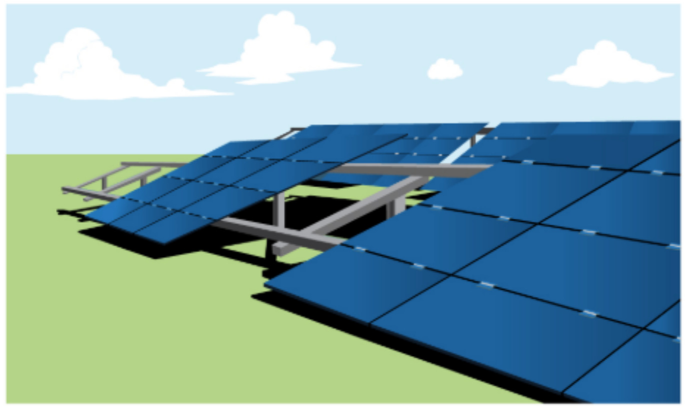



9.2.3. Applied Seamlessly

PV system should be applied seamlessly, and it should be naturally integrated to the building. Natural integration refers to the way that the PV system forms a logical part of the building and how, without a PV system, something will appear to be missing. Generally, the PV modules can be purchased and mounted with a frame or as unframed laminates.

Framed modules can be attached to a framed substrate using traditional fixing methods while laminates can be held in place with laminate clips, or captured by a mullion, as in traditional curtain wall glazing.

In a frameless solar module, the unit is designed in an aesthetically pleasing way while still maintaining the efficiency ratings. In these modules, solar cells are placed between two layers of glass and hence they are also called as 'glass-on-glass' panels. These arrays are placed closer to the roof and they do not have any frames to support them. So, a thick glass is used on the panel to provide structural stability to the installation. Omission of a perimeter frame along the horizontal joints can create the appearance of continuous vertical PV elements. Decorative effects such as fritting have also been incorporated along the edges of frameless modules.



Frameless Modules

9.3 Applications for BIPV

The most common PV application for residential houses is small grid connected rooftop systems from one to 3kWp, which occupy between seven to 15m^2 of roof area.

For commercial buildings, the most popular application is façade or total curtain wall system and atrium roof systems. Retrofits can also use sun shading systems with integrated PV or rain screen claddings to enhance the appearance of the building or flat roof mounting systems, concealed behind the parapet.

BIPV can be used in an infinite number of ways.

9.3.1. Roof Systems

The installation of PV modules on flat roofs is an excellent choice, as the modules can be oriented in the best position, but distance of at least ½ of the height of the structure should be left between the rows of PV modules in order to avoid mutual shading. When installing PV modules on a flat roof, several aspects should be considered:

a. The structure of the roof

b. The elements of the roof as chimneys, exits, skylights, etc.

c. The orientation of the building

When PV modules are installed in new buildings, the structure of the roof is calculated according to the load of the installation, but when they are installed on existing buildings, the load bearing capacity of the structure should be checked. In some case, the roof structure should be reinforced according to the requirements of the building regulations.

Flat Roof or Ground Mounted PV

On sloped roofs, the PV array is typically mounted on fixed racks, parallel to the roof for aesthetic reasons and stood off several inches above the roof surface to allow airflow that will keep them as cool as practical.

Sloped Roof PV Mounting Arrangement

PV Installation on Roof

Roof Integrated Solar Panels

Flexible thin-film amorphous silicon BIPV shingles can replace PV panels. This BIPV product is nailed to the roof deck, very much the way that traditional asphalt shingles are attached to a roof. Also available are fiber cement PV roofing shingles measuring 16 in. by 12 in. by 1/4 in. and weighing 5 pounds.

As an exterior insulation BIPV roof system, PV laminates are attached to polystyrene insulation, and it provides thermal insulation rated R-10 or R-15. It rests on the waterproof membrane without penetrating or being mechanically fastened to the building. In an interlocking tongue-and-groove assembly, the panels are weighed down by pavers that surround the system to provide access for maintenance and repairs.

Film Type Solar Panels

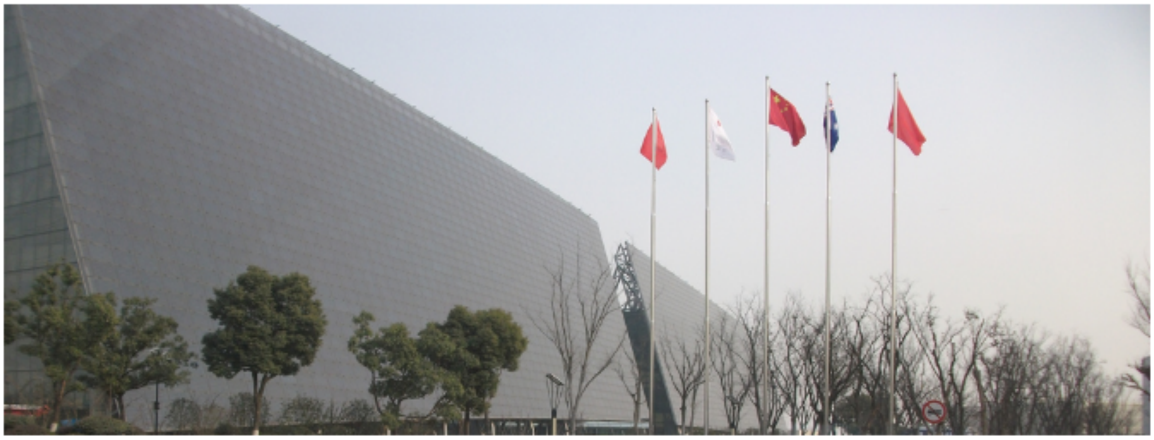
9.3.2. Façade and Window Glazing

In multi-storey buildings due to limited roof spaces, the PV can be integrated into the sides of buildings, replacing traditional glass windows with semi-transparent thin-film or crystalline solar panels. These surfaces have less access to direct sunlight than rooftop systems, but typically offer a larger available area.

Most manufacturers use thin film photovoltaic (PV) technology for manufacturing solar glass. The thin film technology that is used in these panels has been specifically designed for BIPV applications. This offers advantages to the solar glass in terms of performance in the following ways:

a. They perform well even at poor angle of solar incidence
b. Thin film solar cells are efficient even when they are not placed at an optimal angle with direct sunlight. This increases their total available space for installation, and they can therefore be placed vertically on buildings and still perform with good overall efficiency.
c. Thin film solar cells can operate in limited sunlight. This means they can perform well over a greater number of hours per day and hence over the course of the year, resulting in a great energy output.
d. High temperatures hardly impact these panels and they work superlatively over a greater temperature range. This gives them advantage of a good energy production.
e. A big plus of these panels is that they are tough and rigid, with laminated glass that works to increase the overall functionality of the glazing.
f. A recent design by the company Polysolar has a layer of thin PV embedded in the solar glass. The design costs $250 per square meter. It works at an efficiency level of 12% to 15%, which is more than a standard thin film solar panel.

Refer below a photograph of a solar integrated curtain wall.



BIPV Curtain Wall (Suntech, China)

A curtain wall made of BIPV panels is an exterior wall that provides no support to the actual building. In retrofit applications, PV panels can also be used to camouflage unattractive or degraded building exteriors.

The efficiency of the PV modules on facades compared to PV modules on roofs in the same building is at least 30% lower.

PV Panels as Awning or Hangings

PV panels can be used as hanging above windows which will also act as shading devices. They can be independent from the building envelope, incorporated in the building envelope as a curtain wall, or an additional element of the building as a canopy.

This solution is suitable both for new and existing buildings.

It provides:

a. Passive cooling
b. Daylight control, as the best inclination for PV modules is the same as for providing most shadow
c. Electricity production

PV as Shading Device

PV modules can be integrated in many services, as for example:

a. Bus stops

b. Car parks

c. Roofs of railway or bus stations

d. Sound barriers

e. Information boards

f. Streetlights etc.

PV as Shading & Sheltering Application

9.3.3. Ground installations

a. In ground systems you have fixed installation, which are typically mounted on racks and poles. These are used for large areas where the PV panels are oriented for optimal solar exposure
b. Some ground Installations is equipped with tracking systems, where the PV panels follow the sun throughout its apparent movement in the sky.

Rack and Pole mounted Arrays

Solar modules can be mounted to serve a patio cover. This provides shade to the patio area without taking up valuable yard space. It also provides an alternative to roof mounting. This is especially important in areas where concrete or tile roofs are common since it can be very difficult and costly to roof mount to tile roofs.

PV mounted on Patio Cover

9.4 Challenges to BIPV Technology

The most important challenge of BIPV systems is the preservation of the buildings character. BIPV installation is more complicated than regular solar panel installations. The integration of PV modules will probably require the construction of new support structures. The latter may not be possible, due to increases of structural loads that can damage the existing buildings' structure and materials and pose risks for the users. Designers need to pay attention to details for fixing and supporting the PV modules.

On houses, the position, form and proportion of PV arrays within the surrounding roofing material need to be considered. Placing the array directly along the gutter or ridgeline is usually a visually unsatisfactory solution. On the other hand, centering the array between the ridge and gutter line is also not appropriate if only a sliver of roof is being left top and bottom. If the distance between ridge and gutter line is limited, a longer and more narrowly shaped array should be developed. The adoption of a set of proportioning guidelines by councils could assist control of rooftop aesthetics.

The other challenge is the efficiency. BIPV systems are relatively less efficient than conventional PV systems. The lower output is due to the following reasons:

a. Module Level – cell color, glass thickness, and age of solar cells.
b. Array (system) level – angle, orientation, and proximate shading.

c. A limitation of PV technology which often occurs in BIPV systems is when a module string becomes less efficient if one part of it is shaded.

The extent of PV coverage very much depends on latitude and building orientation. Careful attention must be paid especially to east or west-facing vertical building surfaces that require protection from sometimes very harsh morning or afternoon sun. Façades are prone to external shading effects and careful site evaluations and shade modeling is recommended to determine solar access.

Finally, the other important challenge is possible restrictions from building codes and regulations may exist, not allowing the alteration of the building's envelope. It is wise to contact the relevant buildings authorities and check if per-mission for this type of interventions can be given.

9.4.1. Maintenance

PV has no recurring fuel costs, and it is promoted as a simple energy technology that is durable and relatively maintenance- free because it has no moving parts. However, designers should ensure that BIPV installations allow easy access for inspecting, repairing, cleaning and replacing components.

The performance of a BIPV system can decline, if it is in a particularly dirty urban environment. Layers of grime, caused by fuel exhaust and other emissions, can accumulate on a system. Such systems may require periodic cleaning with chemical agents to maximize the system's electrical output. Consequently, system designers must ensure adequate access to the system to perform these maintenance activities.

9.4.2. Percentage of degradation in PV Efficiency

Efficiency does degrade over time due to several conditions, and in most cases it is reversible. Inefficiency is mostly brought about by climatic conditions such as dust and heat which similarly comprise the quality and efficiency of other building systems. Meanwhile efficiency degradation testing is standard procedure for all new manufactured systems, where PV panel testing is routinely checked and tested under normal conditions, however, leveling the testing field has not been very fruitful in bringing concrete guarantees within the PV industry.

Meanwhile, degradation of PV panels typically occurs on the cellular level and many studies place the rate at 0.5-0.7% annually. As a result, some manufacturers of solar panels now offer a 25-year warranty with 82% of the nominal output right after.

9.4.3. Cleaning

Regular cleaning of PV panels is a certain limitation. Recommended cleaning for roof-top panels is 2 – 3 weeks and for near or on the ground panels are once every 10 days due to proximity to vehicular traffic.

9.4.4. Flammability

PV panels are flammable and in case of fire, they will burn, despite being largely composed of silicon. Fire risk mitigation is typically carried out during the design phase where the panel strings are laid out in a series which limits voltage to not more than a 600 or 1000V. This is an industry standard set for optimum efficiency and safety.

9.5 Warranties & Costs

Most modules are very durable, long lasting and can withstand severe weather, including extreme heat, cold and hailstorms. Reflecting this longevity, the most PV manufacturers offer power production warranties for as long as 10, 20, and 25 years. These manufacturers will replace the power output lost from modules that fail to produce at least 80% of the minimum power output specified on the back of the module. This warranty dates from the sale of the product to the original purchaser and is generally non-transferrable.

9.5.1. Product Warranties

It is common these days to see warranties on PV modules of 20 or more years. Although this is impressive and indicates the level of confidence manufacturers place in the longevity of their products, there are many other components in these systems that may not have the same life expectancy. Inverters may have 10-year, five year, or even one-year warranties. This must be considered when reviewing the cost of inverters and other system components.

9.5.2. System Warranties

It is equally important to look for entire system-level warranties of 5 years or more. This indicates that the manufacturer has taken many other operational issues into account. Since these systems generate electrical power, it is helpful to have system performance included as part of the warranty. For instance, a typical system level warranty might state that the system is guaranteed to produce two kilowatts (2 kW) of AC power at Standard Test Conditions (STC) in the fifth year of operation. The equipment to perform this test is expensive, but the fact that a company would know enough to specify this type of warranty is an indication that they are confident in their system design. The intent of this requirement is to improve customer acceptance of PV systems.

9.5.3. Cost of a Solar PV System

The cost of your solar PV system will depend on many factors: system configuration, equipment options, labor cost and financing cost. Prices also vary depending on factors such as whether or not your home is new, and whether the PV modules are integrated into the roof or mounted on the roof. The cost also depends on the system size or rating, and the amount of electricity it produces.

Generally, solar PV systems entail high capital costs. With solar power, you can save on the purchase of electricity from the grid. But even with these savings, it will take a long time to recover the capital cost of the solar PV installation. The operating costs for solar PV installations are negligible, but the annual maintenance cost beyond the warranty period may amount to 0.5% to 1% of the capital cost of the installation.

An optimal PV installation – with the right orientation and placement – has a payback period of 4- 5 years. Studies on BIPV systems show an ROI of 10 -15 years, which is usually a result of aesthetic application taking precedence over energy generation; a choice ultimately made by the building owner, who wants to highlight the presence of the sustainable feature on the building but is not concerned with an immediate ROI. The important thing to note here is that the cost of solar PV has historically been falling by about 4% a year, and if this continues, the ROI can be within 5-10 years.

As per current scenario, thin film modules have lower costs than crystalline silicon modules for modules of similar powers. For updates on module prices refer to the Solarbuzz website at http://www.solarbuzz.com/ModulePrices.htm.

Summary

Photovoltaic (PV) cells create electricity from sunlight by converting photons into electrons without creating any environmental problems such as pollution and waste. Photovoltaic (PV) cells are made of special materials called semiconductors such as silicon (Si), which is currently the most commonly used. Crystalline silicon has been the workhorse of the PV cells for the past two decades and in fact, over 95% of the solar cells produced worldwide are composed of crystalline silicon. However, recent developments in solar cell technologies have produced thin-film and other types of photovoltaic cells with greater conversion efficiencies.

There are many different "types of photovoltaic cell" available on the market, but an individual photovoltaic solar cell produces less than 2 watts of power, which may be sufficient to power a calculator or a wrist watch, but to generate any meaningful solar power that we can use as an alternative power source, individual solar cells need to be combined together to create modules, panels or large solar arrays.

When integrating PV technology with building envelope, the most important issue for the architect is to become fully conversant with the capabilities of the PV cell typologies and comfortable in finding creative integration possibilities at the early stages of design. There are many of BIPV systems, if implemented practically and cost effectively. The positive benefits, which the technology can provide are that it can be used as building material, weather barrier, shade source, aesthetic feature, and most importantly, and finally, as a source of onsite renewable energy. There are other factors that will limit the size of your solar photovoltaic system some of the most common are roof space, budget, local financial incentives and local regulations. When you look at your roof space it is important to take into consideration obstructions such as chimneys, plumbing vents, skylights and surrounding trees. Besides the solar modules, a grid-connected PV system consists of output cables, module mounting structures, AC and DC disconnect switches, inverter(s), grounding equipment and metering system.

As the technologies become more efficient and more mature, a broader palette of module types and integration systems is becoming available to designers. Successful solutions will require an awareness of the parameters of the material and the adoption of a methodology that allows energy, construction, cost and aesthetic factors to be jointly evaluated and modeled at concept level. By gaining an understanding of the primary issues now, building designers will be in a position to evaluate new technologies as they emerge, and to participate in guiding the more widespread adoption of the technology in the future.

Steps for sizing

Estimate the Electric Load

1. Compute the Total connected watts for both AC and DC.
2. Compute the Average Daily Load for Both AC and DC.

Specifying an Inverter

3. Compute the Total AC connected watts.
4. Specify an Inverter to supply the AC Total connected watts.

Battery Sizing

5. Establish the Inverter Losses.
6. Divide the AC Average Daily Load by the Inverter efficiency.
7. Add the result in (6) to the DC Average Daily Load.
8. Divide the result in (7) by the system voltage to get ‘Average Amp Hour Day Load’.
9. Divide the result in (8) by the Days of Autonomy.
10. Divide the result In (9) to get the’ Total Amp Hour Capacity’ of the System.
11. Specify a battery and divide the Total Connected watts by the battery’s rated its Amp Hour to get the Batteries needed to be connected in Parallel.
12. Divide the DC system voltage by the battery voltage to get the batteries wired in series.
13. Multiply (11) and (12) to get the Total number of batteries needed.

Array Sizing

14. Establish the battery energy efficiency.
15. Divide the Amp hour day Load by the battery efficiency.
16. Divide the result in (15) by the ’Peak Sun Hours’ to get ‘Total Array Peak Amps’.
17. Specify a module and divide the Array peak amps by the Peak amps produced by each module to get the Modules needed in parallel.

18. Divide the Dc system voltage by the nominal module voltage to get the Modules in Series.
19. Multiply the result in (17) by that in (18) to get the Total number of modules needed.

Specifying a Controller

20. Multiply the module short circuit current by the total number of module to get the minimum Amp rating for the Charge Controller.

Annexure -1

Typical Power Consumption Demands of Various Appliances

Typical Power Consumption Demands	
Appliance	**Watts**
Coffee Pot	200
Coffee Maker	800
Toaster	800-1500
Blender	300
Microwave	600-1500
Hot Plate	1200
Washing Machine Automatic	500
Washing Machine Manual	300
Vacuum Cleaner Upright	200-700
Vacuum Cleaner Hand	100
Sewing Machine	100
Iron	1000
Clothes Dryer Electric	400
Clothes Dryer Gas heated	300-400
Water Pump	250-500
Ceiling Fan	10-50
Table Fan	10-25
Electric Blanket	200
Blow Dryer	1000
Shaver	15
Computer Laptop	20-50
Computer PC	80-150
Computer Printer	100

Typewriter	80-200
TV 25" Color	150
TV 19" Color	70
1TV 2" B&W	20
VCR	40
CD Player	35
Stereo	10-30
Clock Radio	1
Satellite Dish	30
CB Radio	5
Electric Clock	3
Lights: 100W Incandescent	100
Lights: 25W Compact Fluorescent	28
Lights: 50W DC Incandescent	50
Lights: 40W DC Halogen	40
Lights: 20W Compact Fluorescent	22
Compact Fluorescent Incandescent: 40-watt equivalent	11
Compact Fluorescent Incandescent: 60-watt equivalent	16
Compact Fluorescent Incandescent: 75-watt equivalent	20
Compact Fluorescent Incandescent: 100-watt equivalent	30
1/4" Drill	250
1/2" Drill	750
1" Drill	1000
9" Disc Sander	1200

3" Belt Sander	1000
12" Chain Saw	1100
14" Band Saw	1100
7-1/4" Circular Saw	900
8-1/4" Circular Saw	1400
Refrigerator/Freezer 20cf 1.8Kwh per day (15 hours)	540
Refrigerator/Freezer 16cf 1.6Kwh per day (13 hours)	475
Sun frost 16cf DC (7 hours)	112
Sun frost 12cf DC (7 hours)	70
Freezer 14cf (15 hours)	440
Freezer 14cf (14 hours)	350
Sun frost Freezer 19cf (10 hours)	112

Annexure -2

Sun Hours Available Per Day for US

Source: The Department of Energy's “National Renewable Energy Laboratory (NREL)”

State, City	Summer Avg.	Winter Avg.	Year Avg.
AL, Montgomery	4.69	3.37	4.23
AK, Bethel	6.29	2.37	3.81
AK, Fairbanks	5.87	2.12	3.99
AK, Mantanuska	5.24	1.74	3.55
AZ, Page	7.3	5.65	6.36
AZ, Phoenix	7.13	5.78	6.58
AZ, Tucson	7.42	6.01	6.57
AR, Little Rock	5.29	3.88	4.69
CA, Davis	6.09	3.31	5.1
CA, Fresno	6.19	3.42	5.38
CA, Inyokem	8.7	6.97	7.66
CA, La Jolla	5.24	4.29	4.77
CA, Los Angeles	6.14	5.03	5.62
CA, Riverside	6.35	5.35	5.87
CA, Santa Maria	6.52	5.42	5.94
CA, Soda Springs	6.47	4.4	5.6
CO, Boulder	5.72	4.44	4.87
CO, Granby	7.47	5.15	5.69
CO, Grand Junction	6.34	5.23	5.86
CO, Grand Lake	5.86	3.56	5.08
D. C. Washington	4.69	3.37	4.23
FL, Apalachicola	5.98	4.92	5.49

FL, Belle Island	5.31	4.58	4.99
FL, Gainesville	5.81	4.71	5.27
FL, Miami	6.26	5.05	5.62
FL, Tampa	6.16	5.26	5.67
GA, Atlanta	5.16	4.09	4.74
GA, Griffin	5.41	4.26	4.99
HI, Honolulu	6.71	5.59	6.02
IA, Ames	4.8	3.73	4.4
ID, Twin Falls	5.42	3.41	4.7
ID, Boise	5.83	3.33	4.92
IL, Chicago	4.08	1.47	3.14
IN, Indianapolis	5.02	2.55	4.21
KS, Dodge City	4.14	5.28	5.79
KS, Manhattan	5.08	3.62	4.57
KY, Lexington	5.97	3.6	4.94
LA, Lake Charles	5.73	4.29	4.93
LA, New Orleans	5.71	3.63	4.92
LA, Shreveport	4.99	3.87	4.63
LA, Baton Rouges	4.98	3.80	4.61
MA, Blue Hill	4.38	3.33	4.05
MA, Boston	4.27	2.99	3.84
MA, E. Wareham	4.48	3.06	3.99
MA, Lynn	4.6	2.33	3.79
MA, Natick	4.62	3.09	4.1
MD, Silver Hill	4.71	3.84	4.47
ME, Caribou	5.62	2.57	4.19
ME, Portland	5.2	3.56	4.51

MI, E. Lansing	4.71	2.7	4
MI, Sault Ste. Marie	4.83	2.33	4.2
MN, St. Cloud	5.43	3.53	4.53
MO, Columbia	5.5	3.97	4.73
MO, St. Louis	4.87	3.24	3.78
MS, Meridian	4.86	3.64	4.44
MT, Glasgow	5.97	4.09	5.15
MT, Great Falls	5.7	3.66	4.93
MT, Summit	5.17	2.36	3.99
NC, Cape Hatteras	5.81	4.69	5.31
NC, Greensboro	5.05	4	4.71
ND, Bismark	5.48	3.97	5.01
NE, Lincoln	5.4	4.38	4.79
NE, North Omaha	5.28	4.26	4.9
NJ, Sea Brook	4.76	3.2	4.21
NM, Albuquerque	7.16	6.21	6.77
NV, Ely	6.48	5.49	5.98
NV, Las Vegas	7.13	5.83	6.41
NY, Bridge Hampton	3.93	1.62	3.16
NY, Ithaca	4.57	2.29	3.79
NY, New York	4.97	3.03	4.08
NY, Rochester	4.22	1.58	3.31
NY, Schenectady	3.92	2.53	3.55
OH, Cleveland	4.79	2.69	3.94
OH, Columbus	5.26	2.66	4.15
OK, Oklahoma City	6.26	4.98	5.59
OK, Stillwater	5.52	4.22	4.99

OR, Astoria	4.76	1.99	3.72
OR, Corvallis	5.71	1.9	4.03
OR, Medford	5.84	2.02	4.51
PA, Pittsburgh	4.19	1.45	3.28
PA, State College	4.44	2.78	3.91
RI, Newport	4.69	3.58	4.23
SC, Charleston	5.72	4.23	5.06
SD, Rapid City	5.91	4.56	5.23
TN, Nashville	5.2	3.14	4.45
TN, Oak Ridge	5.06	3.22	4.37
TX, Brownsville	5.49	4.42	4.92
TX, El Paso	7.42	5.87	6.72
TX, Fort Worth	6	4.8	5.83
TX, Midland	6.33	5.23	5.83
TX, San Antonio	5.88	4.65	5.3
UT, Flaming Gorge	6.63	5.48	5.83
UT, Salt Lake City	6.09	3.78	5.26
VA, Richmond	4.5	3.37	4.13
WA, Prosser	6.21	3.06	5.03
WA, Pullman	6.07	2.9	4.73
WA, Richland	6.13	2.01	4.43
WA, Seattle	4.83	1.6	3.57
WA, Spokane	5.53	1.16	4.48
WV, Charleston	4.12	2.47	3.65
WI, Madison	4.85	3.28	4.29
WY, Lander	6.81	5.5	6.06

Province, City			
Alberta, Edmonton	4.95	2.13	3.75
Alberta, Suffield	5.19	2.75	4.1
British Columbia, Kamloops	4.48	1.46	3.29
British Columbia, Prince George	4.13	1.33	3.14
British Columbia, Vancouver	4.23	1.33	3.14
Manitoba, The Pas	5.02	2.02	3.56
Manitoba, Winnipeg New Brunswick	5.23	2.77	4.02
Fredericton	4.23	2.54	3.56
Newfoundland, Goose Bay	4.65	2.02	3.33
Newfoundland, St. Johns	3.89	1.83	3.15
Northwest Territory, Fort Smith	5.16	0.88	3.29
Northwest Territory, Norman Wells	5.04	0.06	2.89
Nova Scotia, Halifax	4.02	2.16	3.38
Ontario, Ottawa	4.63	2.35	3.7
Ontario, Toronto	3.98	2.13	3.44
Prince Edward Isl., Charlottetown	4.31	2.29	3.56
Quebec, Montreal	4.21	2.29	3.5
Quebec, Sept-Isles	4.29	2.33	3.5
Saskatchewan, Swift Current	5.25	2.77	4.23
Yukon, Whitehorse	4.81	0.69	3.1

Annexure -3

Stand Alone PV System Sizing Worksheet (Example)

Application: Stand alone camp system 7 miles off grid

Location: Baton Rouge, La **Latitude:** 30.45 N

SYSTEM INPUTS & PRELIMINARY PRODUCT DATA

1. List of appliances and daily usage

a. 5 lights (30w each), combined rated wattage 150, and used 2 hours/day.

b. Refrigerator, rated wattage 500, used 5 hours/day.

c. 3 ceiling fans (45w each), combined rated wattage 135, and used 8 hours/day.

d. Washer, rated wattage, 1500, used 6 hours/week or 0.86 hours/day.

e. Television, rated wattage 200, used 4 hours/day.

f. Toaster, rated wattage 1500, used 0.25 hours/day.

2. Solar PV Data

Shortlist your product and then based on your calculations and analysis, estimate the quantity and configuration (series/parallel) arrangement.

a. Make: Siemens Solar M55 modules

b. Power = 53 Watts ---[at STC i.e. 1000 watts/m^2 and 25°C]

c. Current = 3.05 amps

d. Maximum voltage at STC = 17.4 V

e. Short circuit current (I_{SC}) = 3.27 amps

f. Open circuit voltage = 2.18 V

g. Guaranteed power output = 47.7 watts ---- [Datasheet below shows the nominal power output is 53 watts ± 10%. The guaranteed power output is 90% of this value or 53 x 0.9 = 47.7 watts.

h. Peak sun hours at optimum tilt = 3.8 hours ---- [This figure is obtained from solar radiation data for the design location and array tilt for an average day during the worst month of the year. Refer annexure -2]. You can also obtain insolation data for additional cities @ https://www.nrel.gov/grid/solar-integration-data.html

PV datasheet for this example:

Siemens Solar M55 module specifications

Power Specifications*

Model	**M55**
Power (typical +/- 10%)	53.0 Watts
Current (typical at load)	3.05 Amps
Voltage (typical at load)	17.4 Volts
Short Circuit Current (typical)	3.27 Amps
Oopen Circuit Voltage (typical)	2.18 Volts

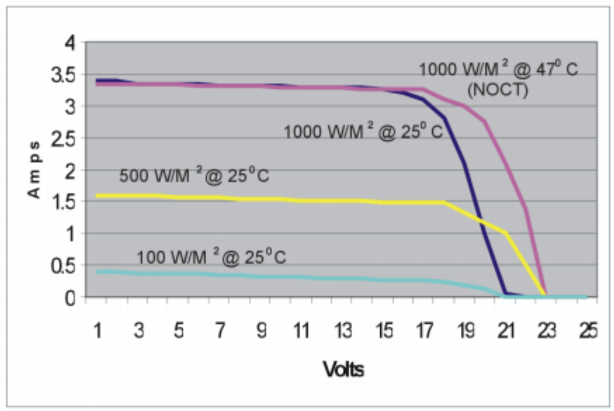
Physical Characteristics

Length	50.9 in/1293 mm
Width	13 in/330 mm
Depth	1.4 in/36 mm
Weight	12.6 lb/5.7 kg

*Power specifications are at standard test conditions of: 1000 W/M², 25° C cell temperature and spectrum of 1.5 air mass.

Performance Characteristics

@ 25° C	
1000 W/M² @ 47° C (NOCT)	



The IV curve (current vs. Voltage) above demonstrates typical power response to various light levels at 25° C cell temperature, and at the NOCT (Normal Cell Operating Temperature), 47° C.

3. Solar Charge Controller

To select an appropriate charge controller, you need to calculate the Controller Input Current and Controller Load Current data.

a. Controller input current comes from the solar array. It is calculated by multiplying short circuit current of PV module by the number of modules in parallel. To be on the safe side, it is recommended to multiply the result by a safety factor of 1.25.

b. Controller load current is the calculated by dividing the total adjusted power rating by the system voltage.

c. Choose a Solar Charge Controller to match the voltage of the PV Array and Batteries.

d. Ensure that the Solar Charge Controller has the capacity to handle the current supplied from the PV system. The size of a controller is determined by multiplying the peak rated current from the module by the modules in parallel. To be conservative, the short-circuit current (Isc) is generally used.

4. Battery Inputs and Specifications

a. Days of storage desired/required = 7 days

b. Depth-of-discharge limit (typical value) = 0.8

c. Make/ Model = Exide 6E95-11 (Deep cycle battery)

d. Battery cell voltage = 12 V

e. Capacity = 478 Amp-hour (Ah)

f. System voltage (battery bus voltage) = 24 V

g. Battery round trip efficiency = 0.85 for efficiency batteries.

Refer Battery Datasheet below:

			20 DAY (480 HR)		10 DAY (240 HR)		5 DAY (120 HR)		3 DAY (72 HR)		
TYPE	VOLTS PER UNIT	NORMAL A.H. CAP	A.H	AMPS	A.H	AMPS	A.H	AMPS	A.H	AMPS	32° F (0° C) 500 HR A.H.
6E95-5	12	180	192	0.40	192	0.80	192	1.60	192	2.67	184
6E95-7	12	270	288	0.60	288	1.20	288	2.40	288	4.00	276
6E95-9	12	360	383	0.80	383	1.60	383	3.19	383	5.32	368
6E95-11	12	450	478	1.00	478	1.99	478	3.98	478	6.64	459
6E120-9	12	500	538	1.12	538	2.24	538	4.48	538	7.47	516
6E120-11	12	625	673	1.40	673	2.80	673	5.61	673	9.35	646
6E120-13	12	750	808	1.68	808	3.37	808	6.73	808	11.22	776
6E120-15	12	875	942	1.96	942	3.93	942	7.85	942	13.08	904
3E120-17	6	1000	1077	2.24	1077	4.49	1077	8.98	1077	14.96	1034
3E120-19	6	1125	1212	2.53	1212	5.05	1212	10.10	1212	16.83	1163
3E120-21	6	1250	1346	2.80	1346	5.61	1346	11.22	1346	18.69	1292
3E120-23	6	1375	1481	3.09	1481	6.17	1481	12.34	1481	20.57	1422
3E120-25	6	1500	1616	3.37	1616	6.73	1616	13.47	1616	22.44	1551
3E120-27	6	1625	1750	3.65	1750	7.20	1750	14.58	1750	24.31	1680
3E120-29	6	1750	1885	3.93	1885	7.85	1885	15.71	1885	26.18	1809

5. Inverter

a. Inverter Input (DC) = 24 V

b. Inverter Output (AC) = 110 V

c. Efficiency = 85%

CALCULATIONS & ANALYSIS

A1	Inverter efficiency	**85%**	Refer input 5c
A2	Battery Bus voltage	**24 volts**	Refer input 5a
A3	Inverter Output AC voltage	**110 volts**	Refer input 5b

LOADS

	A4	**A5**	**A6**	**A7**	**A8**
Appliances	Rated Wattage **(Watts)**	Adjustment Factor **1.0 for DC** **A1 for AC**	Adjusted Wattage (A4/A5)	Hours per day used **(hrs)**	Energy per day **(A6xA7)**
5 x 30 W lights	150	0.85	176	2	**353**
Refrigerator	500	0.85	588	5	**2941**
3 x 45 W fans	135	0.85	159	8	**1271**
Washer	1500	0.85	1765	0.86	**1518**
TV	200	0.85	235	4	**941**
Toaster	1500	0.85	1765	0.25	**441**
Total	**3985**		**4688**		**7463**

A9	Total energy demand per day (watt-hour)	**7463**	Sum of A8
A10	Total energy demand per day (amp-hour)	**311**	Amp-hours are determined by dividing the total energy demand per day (A9) by the battery bus voltage (A2). $\frac{7463 \text{ watt hour}}{24\text{V}} = 311 \text{ amp-hours}$
A11	Maximum rated power of appliances (Watts)	**3985**	Sum of A4
A12	Maximum adjusted power requirement (Watts)	**4688**	Sum of A6

BATTERY SIZING Design Temperature 25°C/ 77°F

B1	Days of storage desired/required (autonomy)	7.0	Refer inputs 4a
B2	Allowable depth-of-discharge limit (decimal)	0.8	Refer inputs 4b
B3	Required battery capacity (amp – hours)	2721	(A10 x B1) / B2 $\frac{311 \times 7}{0.8}$ = 2721 amp-hours
B4	Amp-Hour capacity of selected battery Note -1	478	Refer inputs 4e Note -1 below
B5	Number of batteries in parallel	6	B3 / B4 (Round it to higher integer) $\frac{2721}{478}$ = 5.7 or 6
B6	Number of batteries in series	2	A2 / Selected Battery voltage ----[refer inputs 4d] $\frac{24}{12}$ = 2
B7	Total Number of Batteries	12	B5 x B6 6 x 2 = 12
B8	Actual installed total battery amp-hour capacity (amp-hours)	2868	B4 x B5 478 x 6 = 2868

Note 1: Amp-hour capacity of selected battery.

Once the required number of amp-hours has been determined (B3), batteries or battery cells can be selected using manufacturers' spec sheet.

PV ARRAY SIZING

C1	Total energy demand per day (watt-hours)	7463	= A9
C2	Battery round trip efficiency	0.85	Refer inputs 4g
C3	Required array output per day (watt-hours)	8780	C1 / C2 $\frac{7463}{0.85}$ = 8780
C4	Selected PV module max power voltage at STC (Volts)	14.8	V_{max} x 0.85 – [Refer inputs 2d for V_{max}] 17.4 x 0.85
C5	Selected PV module guaranteed power output	47.7	Manufacturer's datasheet. Refer inputs 4g

	at STC (watts)		
C6	Peak sum hours at design tilt for design month (hours)	3.8	Solar Intensity data. Refer inputs 2h
C7	Energy output per module per day (watt-hours)	181	C5 x C6 47.7 x 3.8 = 181
C8	Module energy output at operating temperature (watt-hours)	163	DF x C7 ---[DF =0.9] 0.9 x 181 = 163
C9	Number of modules required to meet energy requirements (modules)	54	C3 / C8 (Round off to next higher integer) $\frac{8780}{163}$ = 53.8 or 54
C10	Number of modules required per string rounded to the next higher integer.	2	A2 / C4 (Round off to next higher integer) $\frac{24}{148.8}$ = 1.62 or 2
C11	Number of modules in parallel rounded to the next higher integer.	27	C9 / C10 (Round off to next higher integer) $\frac{54}{2}$ = 27
C12	Number of modules to be purchased	54	C10 x C11 (Round off to next higher integer) 2 x 27 = 54
C13	Nominal rated PV module output (watts)	53	Manufacturer data, Refer inputs 2b
C14	Nominal rated array output (watts)	2862	C12 x C13 54 x 53 = 2862

INVERTER SIZING

The input rating of the inverter should never be lower than the total watt of the appliances. The inverter must have the same nominal voltage as your battery. Maximum adjusted wattage = 4688 Watts ----- [Refer A12]

Add 25% safety margin to account for surge requirements.

Inverter capacity = 4688 x 1.25 = 5860 Watts

So the minimum required inverter size equal to say 6000 Watts or 6 kW

Inverters are typically specified in VA or kVA, which is Watts or kW divided by power factor of the system. Assume an average power factor of 0.95 ---- [Power factor is less than unity due to inductive loads of motors, refrigerator compressors etc. For resistive loads such as toasters the power factor is 1].

CONTROLLER SIZING

Calculate PV Array Current (Minimum Controller Input Current)

PV Array Current = I_{SC} x PV_P x Safety Factor

- I_{SC} = Module short circuit current = 3.27 amps ---------[The Siemens 53 Watts solar panel has a short circuit current of 3.27 Amp. Refer inputs 2e].
- PV_P = PV modules in parallel = 27 no. ----------- [Refer C11].
- Safety Factor = 25%

PV Array Current = 3.27 amps x 27 x 1.25 = 110.36 say 111 amps

Calculate Load Current (Minimum Controller Output Current)

Max. DC load current = Total adjusted power (Watts)/ DC System Voltage

Total adjusted power = 4688 Watts----- [Refer A12]

System Voltage = 24 V------[Refer 4f]

Max. DC load current = 4688 W / 24 V = 195.33 say 196 amps

So that the charger controller should be rated 111 amps input and 196 amps output current or little bit greater.

CABLE SIZING

When the size and type of wire are well selected this improves reliability and performance of PV system that is why cable sizing is a very important step. In this system we used copper wire.

The cables cross sectional are determined by the following equation:

$$A = \frac{p \times L \times I \times 2}{V_d}$$

Where:

- p=resistivity of wire ----- [For copper p = $1.724 \times 10^{-8}\ \Omega \cdot m$]

- L = length of wire (in m)
- A = cross sectional area of cable in mm^2
- I =the rated current of regulator, amps
- V_d =Voltage drop, volts

In both AC and DC wiring, the voltage drop is taken not to exceed 4 % value.

i. Cable Size between PV Array and Charge Controller

Voltage Drop (4% minimum)

$V_d = \frac{4}{100} \times V_{module}$

$V_d = \frac{4}{100} \times 24V = 0.96V$

$A = \frac{p \times L \times I \times 2}{V_d}$

$P = 1.724 \times 10^{-8}\ \Omega \cdot m$

Let the length of the cable be 1m

I_{max} = 111 amps

$A = \frac{1.724 \times 10^{-8} \times 1 \times 111 \times 2}{0.96} = 3.98\ mm^2$

This means that any copper cable of cross sectional area 3.98 mm^2, 111 amps and resistivity 1.724 $\times 10^{-8}$ Ω .m can be used for the wiring between PV array and input to the charge controller.

ii. Cable Size between Charge Controller and Battery

Voltage Drop (4% minimum)

$V_d = \frac{4}{100} \times V_{module}$

$V_d = \frac{4}{100} \times 24V = 0.96V$

$A = \frac{p \times L \times I \times 2}{V_d}$

$P = 1.724 \times 10^{-8}\ \Omega \cdot m$

Let the length of the cable be 5 m

I_{Rated} = 196 amps

$$A = \frac{1.724 \times 10^{-8} \times 5 \times 196 \times 2}{0.96} = 3519.83 \times 10^{-8} = 35.2\ mm^2$$

This means that any copper cable of cross sectional area 35.2 mm^2, 196 amps and resistivity 1.724 $\times 10^{-8}$ Ω. m can be used for the wiring between charge controller and batteries.

iii. Cable Size between the Battery Bank and the Inverter

At full load, the batteries maximum current I_{max} is given by:

$$I_{max} = \frac{\text{Inverter watts}}{V_{system}}$$

Inverter capacity = 6000 watts

System voltage (V_{system}) = 24V

$$I_{max} = \frac{6000\ \text{watts}}{24V} = 250\ \text{amps}$$

Voltage Drop (4% minimum)

$$V_d = \frac{4}{100} \times V_{module}$$

$$V_d = \frac{4}{100} \times 24V = 0.96V$$

Cross-section area of cable

$$A = \frac{p \times L \times I \times 2}{V_d}$$

$P = 1.724 \times 10^{-8}\ \Omega \cdot m$

Let the length of the cable be 8m

$$A = \frac{1.724 \times 10^{-8} \times 8 \times 250 \times 2}{0.96} = 7183.33 \times 10^{-8} = 71.83\ mm^2$$

This means that any copper cable of cross sectional area of 71.83 mm^2, 250 amps, and resistivity 1.724 x 10^{-8} Ω .m can be used for the wiring between the battery bank and inverter.

iv. Cable Size between the Inverter and Load

The phase current in 3 phase, AC supply from inverter is given by equation:

$$I_{phase} = \frac{\text{Inverter, watts}}{V\ out \times \sqrt{3} \times \text{Power factor}}$$

- Inverter output = 6000 watts
- V output = 110V
- Power factor = say 0.9
- $\sqrt{3} = 1.732$

$I_{phase} = \frac{6000}{110 \text{ x } 1.732 \text{ x } 0.9} = 34.9 \; or \; say \; 35 \; amps$

Voltage Drop (4% minimum)

$V_d = \frac{4}{100} \text{ x } V_{Out}$

$V_d = \frac{4}{100} \text{ x } 110V = 4.4V$

Cross-section area of cable

$A = \frac{p \text{ x } L \text{ x } I \text{ x } 2}{V_d}$

$P = 1.724 \text{ x } 10^{-8} \; \Omega \cdot m$

Let the length of the cable be 24m

$A = \frac{1.724 \text{ x } 10^{-8} \text{ x } 24 \text{ x } 35 \text{ x } 2}{4.4} = 658.25 \text{ x } 10^{-8} = 6.58 \; mm^2$

This means that any copper cable of cross sectional area of 6.58 mm^2, 35 amps, and resistivity 1.724 x 10^{-8} Ω-m can be used for the wiring between the inverter and load.