Solar Cell, Concept, System Components

Solar Photovoltaic Technologies

- Solar PV is a semiconductor device which coverts sunlight directly into electricity.
- A solar PV panel, when exposed to sunlight generates voltages and current at its output terminal
- The higher is the intensity of the sunlight, the more will be the electricity generated from it,

- The electricity that is generated from a PV module is DC in nature.
- The conversion of DC power to AC power can be achieved using a device called inverter

Solar PV Technology : Advantages & Limitations

- Solar PV technology uses sunlight as input and gives electrical energy as an output, which is a direct conversion of light into electricity.
- Unlike other renewable energy technologies like wind, biomass and solar thermal where other intermediate steps are required to convert an input energy to electricity
- Solar PV technologies use semiconductor materials(having properties in between metals like aluminum and insulator like plastic) for conversion of light into electricity.

- It does not have any moving parts in it and therefore does not require any maintenance or require very little maintenance.
- Renewable energy technologies like biomass, wind energy etc. having moving parts and requires some maintenance.
- Solar PV modules cannot produce electricity during the time when there is no light, like during the night and during cloudy days.

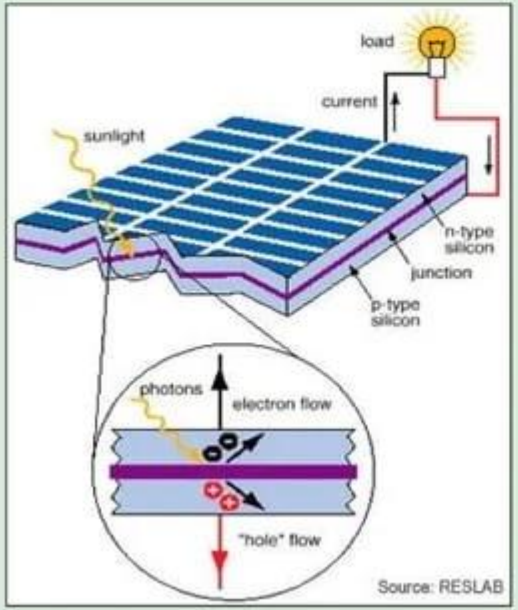
How PV Cells Work?

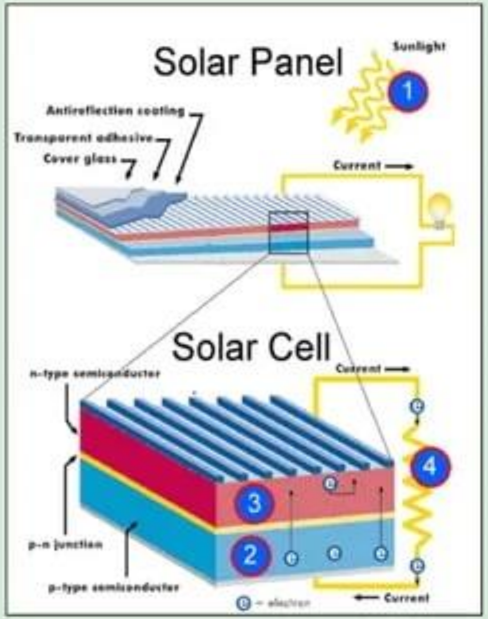
What Are Solar Cells?

- Thin wafers of silicon
  - Similar to computer chips
  - much bigger
  - much cheaper!
- Silicon is abundant (sand)
  - Non-toxic, safe
- Light carries energy <u>into</u> cell
- Cells <u>convert</u> sunlight energy into electric current- they do not store energy
- Sunlight is the "fuel"

- Solar PV modules produce power output proportional to their size.
- A PV module can produce as small as one thousand of a watt (one milli – watt) such small power is required for our wrists watches and calculaters.
- Normally PV modules are available for the sizes from 5 watt to 300 watt.
- For instance, 10,000 solar PV modules of 100 watt would together produce about one megawatt of DC power

WORKING PRINCIPLE





- **Photons** in **sunlight** hit the solar panel and are absorbed by semiconducting materials, such as silicon.
- **Electrons** are knocked loose from their atoms, causing an electric potential difference. Current starts flowing through the material to cancel the potential and this electricity is captured.

- **Due to the special composition of solar cells, the electrons are only allowed to move in a single direction.**
- **An array of solar cells converts solar energy into a usable amount of Direct Current (DC) electricity.**
- **Material used-Si, Cadmium sulphide, Gallium arsenide, etc.**

PV Basics

- A solar cell is a small semiconductor device which has a light sensitive *N-P* junction. When solar light rays strike the *N-P* junction, DC e.m.f. is generated with P terminal as positive and N-terminal as negative.

- Nominal ratings of a typical single PV-cell when exposed to full sun light are:

  - Voltage 0.45 V, DC
  - Current 0.75 A, DC
  - Power 0.33 W

- When exposed to sun light, the solar cell acts like a tiny DC cell. Several Solar cells are connected in series, parallel to get desired voltage, current and power.

Electrical Characteristics of a PV Cell

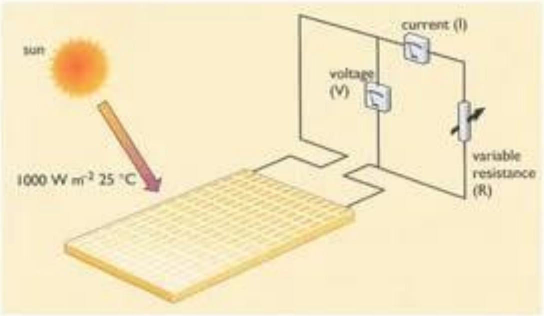


Fig.3 PV cell connected to a variable resistance

Electrical Characteristics of a PV Cell

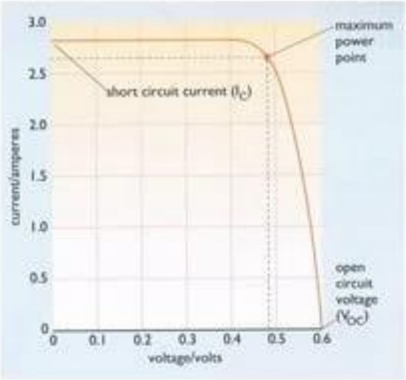
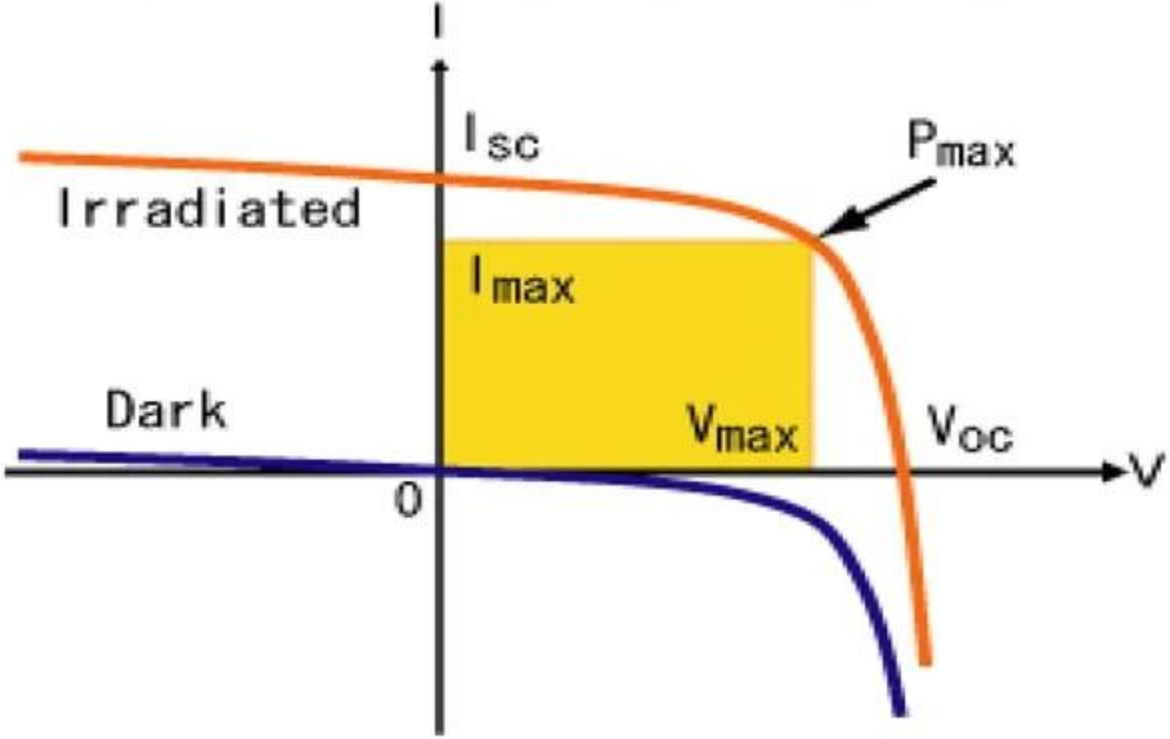


Fig.4 Current-Voltage characteristics of a typical silicon PV cell.

VI CHARACTERISTICS



- The fill factor is defined as the ratio of the actual maximum obtainable power to the product of the open circuit voltage and short circuit current.
- It evaluates the performance of solar cells.

$$FF = I_{max} V_{max} / I_{sc} V_{oc}$$

Maximum Conversion Efficiency

$$\eta_{max} = (I_{max} V_{max}) / (I_T A_c)$$

Where,

I_T = Incident solar flux and

A_c = Area of the cell

Electrical Characteristics of a PV Cell

- The amount of power available from a PV device is determined by;
  - the type and area of the material
  - the intensity of the sunlight; and
  - the wavelength of the sunlight

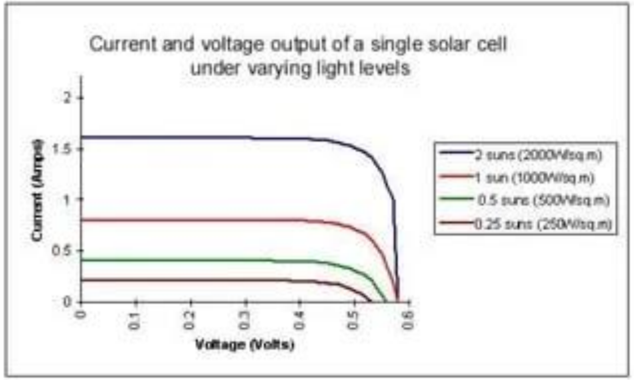


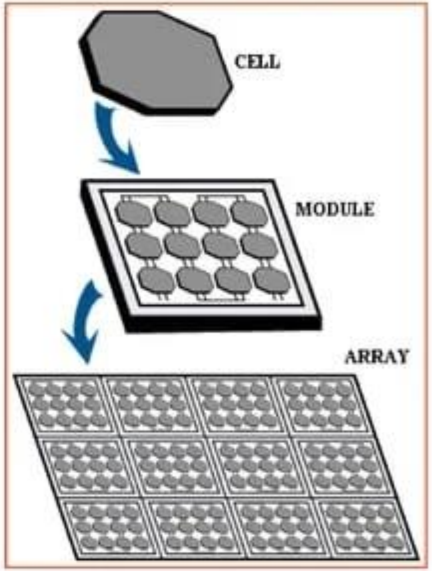
Fig. Current & voltage output of a solar cell at different light intensities

Electrical Characteristics of a PV Cell

- An important feature of PV cells is
  - V does not depend on its size; remains constant with changing light intensity
- But, I $\propto$ light intensity and size
- The power output of a solar cell can be $\uparrow$ by tracking or concentrators

- But, the complexity of the mechanisms + need to cool the cells makes it unfavorable.

PV cells, Modules and Arrays

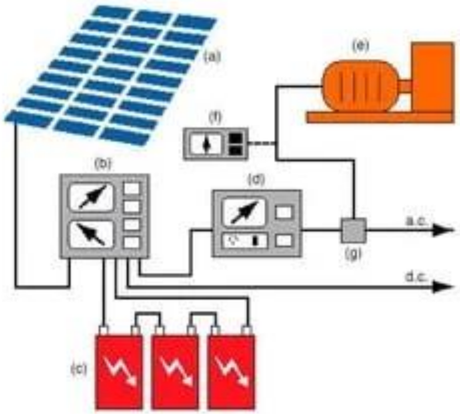


- **Cells** are the building block of PV systems
  - –Typically generate 1.5 - 3 watts of power
- **Modules/**panels are made up of multiple cells
- **Arrays** are made up of multiple modules
  - –A typical array costs about $5 – $6/watt
- Still need lots of other components to make this work
- Typical systems cost about **$8/watt**

Connect Cells To Make Modules

- One silicon solar cell produces 0.5 volt
- 36 cells connected together have enough voltage to charge 12 volt batteries and run pumps and motors
- Module is the basic building block of systems
- Can connect modules together to get any power configuration

Elements of a PV System



(a) a PV panel array, ranging from two to many hundreds of panels;

(b) a control panel, to regulate the power from the panels;

(c) a power storage system, generally comprising of a number of specially designed batteries;

(d) an inverter, for converting the DC to AC power (eg 240 V AC)

(e) backup power supplies such as diesel startup generators (optional)

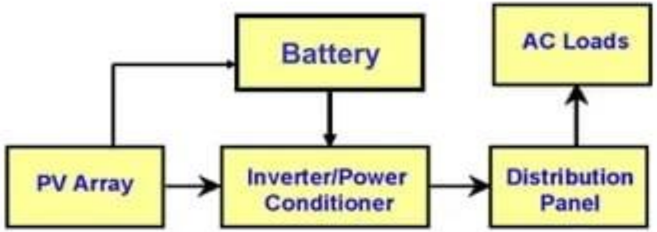
(f) framework and housing for the system

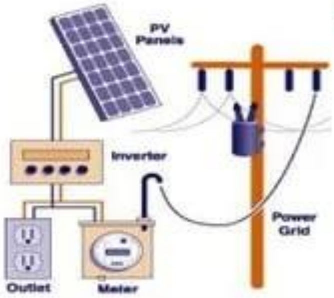
(g) trackers and sensors (optional)

Total system cost = ~Rs. 500 / watt

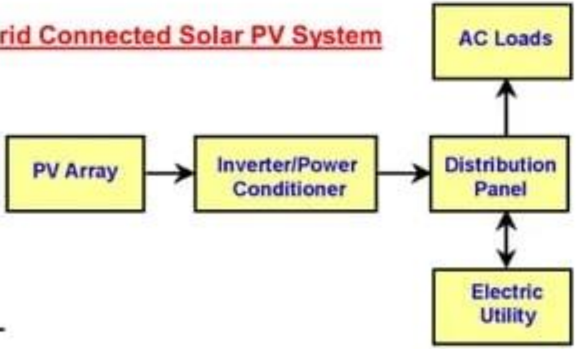
PV Components

Stand Alone Solar PV System





Grid Connected Solar PV System



TYPES

- Mono - crystalline Silicon Cells
- Polycrystalline Silicon Cells
- Amorphous Silicon (Thin-Film)

MONO-CRYSTALLINE SILICON CELLS

- These are made using cells sliced from a single cylindrical crystal of silicon, this is the most efficient photovoltaic technology.
- converting around 15% of the sun's energy into electricity.

MONO-CRYSTALLINE CELLS IN MODULE

POLYCRYSTALLINE SILICON CELLS

- It is known as multi-crystalline cells, these are made from cells cut from an ingot of melted and recrystallised silicon.
- they are generally cheaper to produce than mono-crystalline cells,

POLY-CRYSTALLINE CELLS IN MODULE (PANNEL)

- slightly less efficient, with average efficiencies of around 12%.

AMORPHOUS SILICON (AKA THIN-FILM)

- **Amorphous silicon cells are made by depositing silicon in a thin homogeneous layer onto a substrate.**
- **the cells can be thinner hence it is called as"thin film" PV.**
- **Efficiency is 10%**

Is my site adequate?

There are 3 factors:

- Systems installed must have a southern exposure, for maximum daily power output.
- The southern exposure must be free of obstructions such as trees, mountains, and buildings that might shade the modules (Summer and Winter paths of sun).
- Systems must also have appropriate terrain and sufficient space to install the PV system.

Solar PV Dependencies

- Location, Location, Location !
- Latitude
  - Lower latitudes better than higher latitudes
- Weather
  - Clear sunny skies better than cloudy skies
  - Temperature not important
- Direction solar arrays face
  - South preferred, east and west acceptable
- Absence of shade
  - Trees, Flatirons, etc.
- Module temperature affects the output power

Solar PV Array Design

- Array Flat Panel
  - Remains in a constant fixed position
- Array tilt (equal to latitude best)
  - Increase solar radiation by 10-20% compared to 0% tilt
  - Sunnier locations benefit more
- Array azimuth (180° best)
  - Directly south

Solar PV Array Tracking

- Array 1-axis tracking
  - Tracks sun across the sky during each day
  - Stays at a constant tilt
  - Increase solar radiation by 25-30% compared to no tracking
  - Sunnier locations benefit more
- Array 2-axis tracking
  - Tracks sun across the sky during each day
  - Adjusts tilt – more in winter, less in summer
  - Increase solar radiation by 33-38%
  - Sunnier locations benefit more

How to size the system?

- It is necessary to know the energy needs, which you figure by listing all your daily loads, such as lights, TV, radios or batteries.
- To determine total energy consumption, wattage of the appliance should be multiplied by the number of hours used in a day.
- After adding the totals for each appliance, you can decide what power output you need for your PV system.

Typical Cost of Solar PV Modules

No	PV panel rating watt (peak), Wp	Cost (Rs)
1	10	500
2	20	1000
3	40	2000
4	75	3750

TYPICAL COST OF BATTERIES

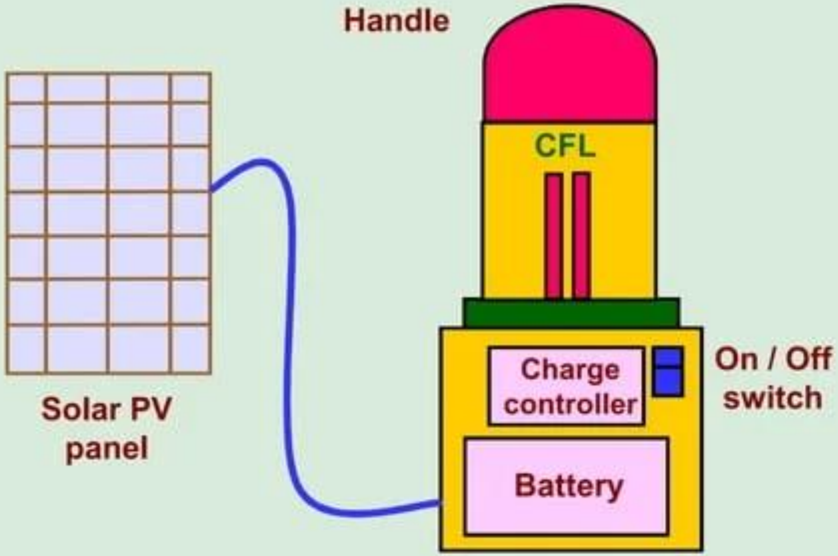
No	Battery rating Amp-hour (Ah)	Voltage rating (volts)	Cost (Rs)
1	40	12	3300
2	60	12	3400
3	90	12	4650
4	110	12	5000
5	150	12	9500

SPECIFICATION OF AN INVERTER

Rated	Power	1000 VA- 3000 VA	5 kVA-8kVA	9 kVA -15 kVA
Input	Voltage	12 V/24 V	24 V/36 V/48 V	36 V/48 V
Output	Voltage	220 V(AC) & 110 V(AC)	220 V(AC) & 110 V(AC)	220 V(AC) & 110 V(AC)
Output	Frequency	50 Hz/60 Hz	50 Hz/60 Hz	50 Hz/60 Hz
Output	Waveform	Full sine wave	Full sine wave	Full sine wave

Typical Cost of Inverter

No	System (kVA)	Cost (Rs)
1	1	5000
2	2	7000
3	3	9000
4	4	12000
5	5	15000



Solar PV Lantern

TYPICAL POWER RATINGS OF COMMON APPLIANCES

Component	Power Rating
CFL (watts)	8 to 18
Fan (watts)	60
Tube + Cu choke (watts)	55
Tube + Electronic choke (watts)	47

In order to design PV system, number of parameters about the component used in the system should be known. Following assumptions can be made (for actual design real data should be obtained):

Assumptions:

1. Inverter converts DC into AC power with an efficiency of about 90 %.
2. Battery charging and discharging cycle efficiency is about 90 %.
3. Also all the charge of a battery cannot be used. And one has to consider maximum depth of discharge of a battery. This can vary widely. Here we are assuming 80 % depth of discharge, meaning only 80 % of the total capacity of the battery is useful.

- The combined efficiency of inverter and battery will be calculated as,

Combined efficiency = inverter efficiency x battery efficiency

= 0.9 x 0.9 = 81 %

- Battery voltage used for operation = 12 volts
- Battery capacity = 120 Ah
- Sunlight available in a day = 8 h / d (equivalent of peak radiation)
- Operation of lights and fan = 6 h/d on PV panels
- PV panel power rating = 40 Wp

Operating factor:

- In the operating condition the actual output power of a PV module is less.
- Thus, a factor called ‘operating factor’ is used to estimate the actual output from a PV module.
- The operating factor can vary between 0.60 and 0.90 and 0.90 (implying that output power is 60 to 80 % lower than rated output power) in normal operating conditions, depending on temperature, dust on module, etc.
- Thus the actual output power of a 40 Wp PV panel

  = 0.75 (operating factor) x 40 = 30 Watt.

- Remember Wp, meaning, watt (peak), gives only peak power output of a PV panel.

A solar PV system design can be done in four steps:

1. Load estimation
2. Estimation of number of PV panels
3. Estimation of battery bank
4. Cost estimation of the system

Steps to design a solar PV system

Step 1 : Find out total energy requirement of the system (total load)

Total connected load to PV panel system

= No. of units x rating of equipments

= 2 x 18 + 2 x 60 = 156 watts

Total watt-hours rating

= Total connected load (watts) x operating hours

= 156 x 6 = 936 watt - hours

STEP 2 : Find out the number of PV panels required

Actual power output of a PV panel

= Peak power rating x operating factor

= 40 x 0.75 = 30 watt

Total power used at the end use is less (due to lower combined efficiency of the system)

= Actual power output of a panel x combined efficiency

= 30 x 0.81 = 24.3 watts (VA)

= 24.3 watts

Energy produced by one 40 Wp panel in a day

= Actual power output x 8 hours / day (peak equivalent)

= 24.3 x 8 = 194.4 watt - hour

Note : *Though the day length can be longer, we consider light equivalent to number of peak hours (1000 W / m^2) for which solar panel is characterized. For exact value one need to look at meteorological data for given location .*

Number of solar panels required to satisfy given estimated daily load (from step 1)

$$= \frac{\text{Total watt-hour rating (daily load)}}{\text{Daily energy produced by a panel}}$$

= 936 / 194.4 = 4.81 = 5 (round figure)

Note : *For system of voltage higher than 12 (say 24), 24/12=2, two modules should be in series to provide 24 volt (while total number of panels should be same)*

STEP 3 **: Find out the battery requirement**

Total amp-hour required (total charge to be stored), (battery size should be higher than the actual useful energy due to less combined efficiency of the system)

$$= \frac{\textbf{Total amp-hour rating}}{\textbf{(battery efficiency x depth of discharge x battery voltage)}}$$

$$= \quad 936 \,/\, 0.9 \times 0.8 \times 12 \quad = \quad 108.33$$

Note : One can also decide to design a system with 24 volt or 48 volt. Since typically PV panels and battery are designed to give 12 volt, series –parallel combination of panels and batteries will be required to get higher PV system voltages.

$$\text{Number of batteries required} = \frac{\text{Total amp-hour rating}}{\text{Battery rating under use}}$$

$$= 108.33 / 120$$

$$= 0.9 \approx 1 \text{ (round figure)}$$

Step 4: Find out inverter size

Inverter rating (watts or VA)

Total connected load to PV panel system = 156 watts

= 156 VA

Inverter are available with rating of 100, 200, 500 VA, etc.

Therefore, the choice of the inverter should be 200 VA

In this way, total load and the requirement of number and size of various solar PV system components can be estimated. The examples taken here are for small size house. For designing solar PV systems for large house or for industrial application similar design approach can be taken.

Cost Estimation of a PV System

Cost estimation of a solar PV system for 2 CFLs and 2 fans for 6 hours per day is done here. The case study of the above section is considered for cost estimation. After finding out the requirement of number and capacity of various systems components, like panels, battery, inverter, it is a trivial job to estimate the cost. One has to just add the cost of all components. But some margin should be taken for other costs like wiring, supporting infrastructure for panel and batteries, etc.

(a) Cost of arrays = No. of PV modules x Cost / Module

= 5 x 2000 (for a 40 Wp panel @ Rs 50 / Wp)

= Rs 10000

(b) Cost of batteries = No. of Batteries x Cost / Battery

= 1 x 7500

= Rs 7500

(c) Cost of Inverter = No. of inverters x Cost / Inverter

= 1 x 5000

= Rs 5000

Total cost of system = A + B + C

= 10000 + 7500 + 5000

= Rs 18000

Additional cost of wiring may be taken as 5 % of total system cost.

Payback Period

- Actual power output of a 40 Wp panel

= PV panel rating x operating factor

= 40 x 0.75 = 30 Wp

- Energy produced by one 40 Wp panel

= Actual power output of a panel x combined efficiency x No. of sun shines per day

= 30 x 0.81 x 8 = 194.4 Watt hour

- The total energy produced by the PV panels in a day

= Energy produced by one 40 Wp panel x No. of panels

Energy

= 194.4 x 5 = 972 Watt-hour = 0.972 kWh

- Cost of electricity for 1 kWh from EB is = Rs. 5

- Therefore cost of electricity produced from PV panels / day

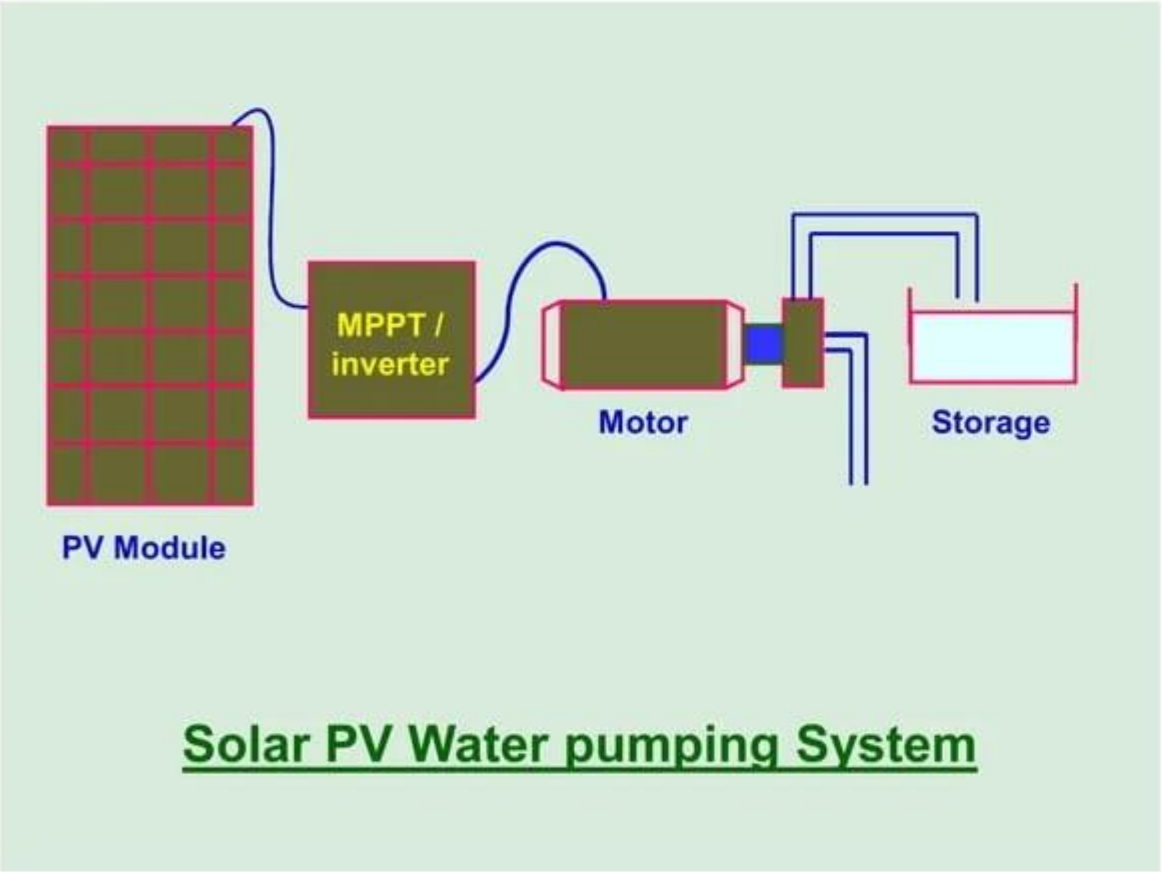
= 0.972 x 5 = Rs. 4.886

- Payback period

  = Total cost of the system / cost of electricity produced from PV panels per day

  = 3683 days

  = 10 years


MPPT / inverter
Motor
Storage
PV Module
Solar PV Water pumping System

SOLAR PV WATER PUMPING SYSTEM

Design of solar PV pumping systems requires knowledge about how much water needs to be pumped, at what depth water should be pumped, how many solar panel will be required for a given water requirement, what should be the ratings of a motor used with PV panels, etc. The overall design of the system can be divided in following steps:

Step 1 : Determine the amount of water required per day

Step 2: Determine the Total Dynamic Head (TDH) for water pumping

Step 3: Determine the hydraulic energy required per day (watt-hour / day)

Step 4 : Determine the solar radiation available at given location in terms of equivalent of peak sunshine radiation (1000 W/m^2) hours for which solar PV module is characterized. Topically this number is 5 to 8 varying season to season and location to location.

Step 5 : Determine the size of solar PV array and motor, consider motor efficiency and other losses.

Before considering a case study, let us look at some of the definitions related to the PV pumping

CASE STUDY

Design of a PV system for pumping 25000 litres of water everyday form a depth of about 10 metre is considered.

The data required for calculations are following and the calculation in given below :

- Amount of water to be pumped per day = 25000 litre = $25 m^3$
- Total vertical lift = 12 metres (5 m – elevation, 5 m – standing water level, 2 m-drawdown)
- Water density = 1000 kg / m^3
- Acceleration due to gravity, g = 9.8 m/s^2
- Solar PV module used = 75 Wp
- Operating factor = 0.75 (PV panel mostly does not operate at peak rated power)
- Pump efficiency = 30 % or 0.30 (can be between 0.25 and 0.40)
- Mismatch factor = 0.85 (PV panel does not operate at maximum power point)

Calculations for PV water pumping system

Step 1 : Determine total daily water requirement

Daily water requirement = 25 m^3 / day

Step 2 : Determine total dynamic head

Total vertical lift = 12 m

Frictional losses = 5 % of the total vertical lift

= 12 x 0.05 = 0.6 metre

Total dynamic head (TDH) = 12 + 0.6 = 12.6

Step 3 : Determine the hydraulic energy required per day

Hydraulic energy required to raise water level

= mass x g x TDH

= density x volume x g x DH

= (1000 kg / m^3) x (25 m^3/day) x (9.8 m/s^2) x 12.6

= (multiply by 1/3600 to convert second in hours)

= 857.5 watt-hour / day

Note : Potential energy of the water is raised due to pumping, which must be supplied to the pump

Step 4 : Determine solar radiation data

Solar radiation data in terms of equivalent peak sunshine radiation (1000 W/m^2) varies between about 5 and 8 hours. For exact hours, meteorological data should be used.

= 6 h / d (peak of 1000 W/m2 equivalent), actual day length is longer (this is equivalent of solar radiation of 180000 watt-hours / month at a given location)

Step 5 : Determine the number of PV panel and pump size

Total wattage of PV panel

$$= \frac{\text{Total hydraulic energy}}{\text{No. of hours of peak sunshine / day}}$$

$= 857.5 / 6 \quad = \quad 142.9$ watt

Considering system losses

$$= \frac{\text{Total PV panel wattage}}{\text{Pump efficiency x Mismatch factor}}$$

$$= 142.9 / 0.3 \times 0.85 \quad = \quad 560 \text{ watt}$$

Consider operating factor for PV panel

$$= \frac{\text{Total PV panel wattage after losses}}{\text{operating factor}}$$

$$= 560 / 0.75 \quad = 747.3 \text{ watt}$$

Number of solar PV panel required of 75 Wp each

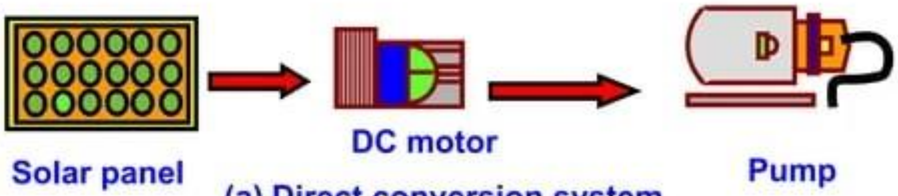
$$= 747.3 / 75 \quad = 9.96 \approx 10 \text{ (round figure)}$$

Power rating of the motor

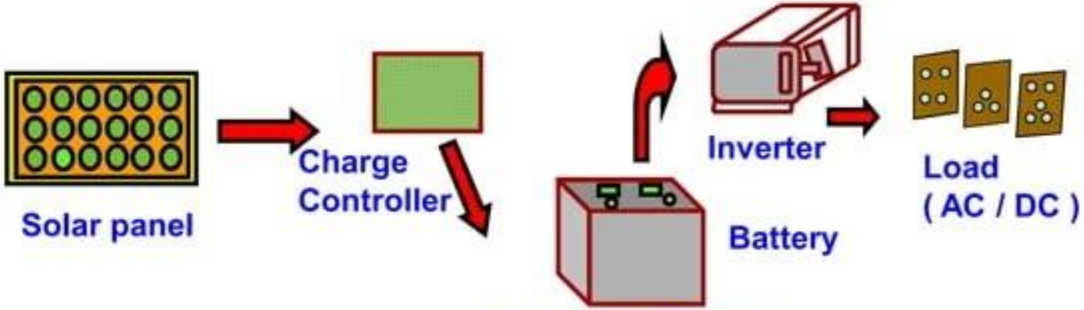
$$= 747.3 / 746 \approx 1 \text{ HP motor}$$

In this way, a solar PV water pumping system can be designed.

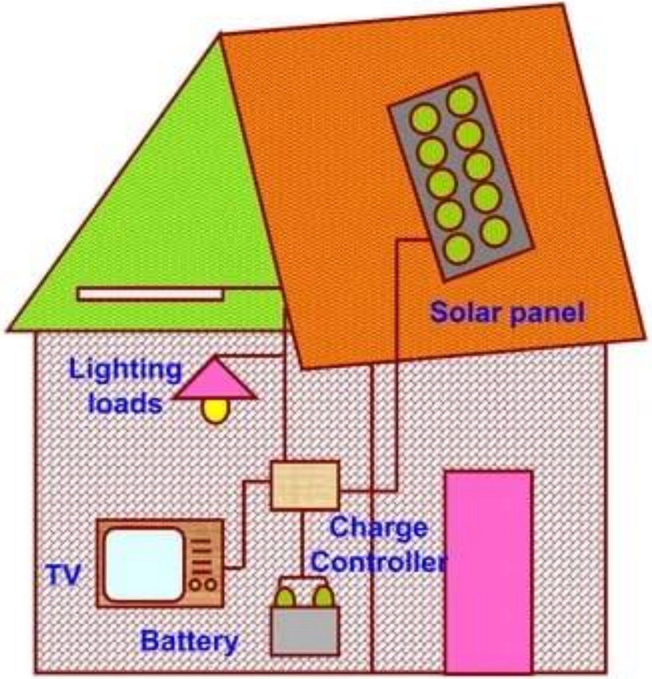
PV System Configurations



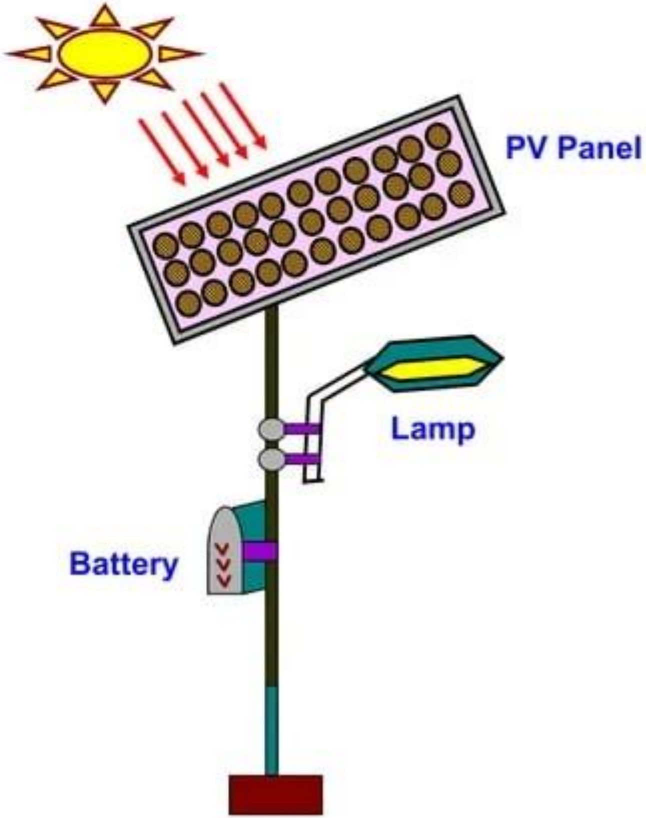
(a) Direct conversion system



(b) Storage System

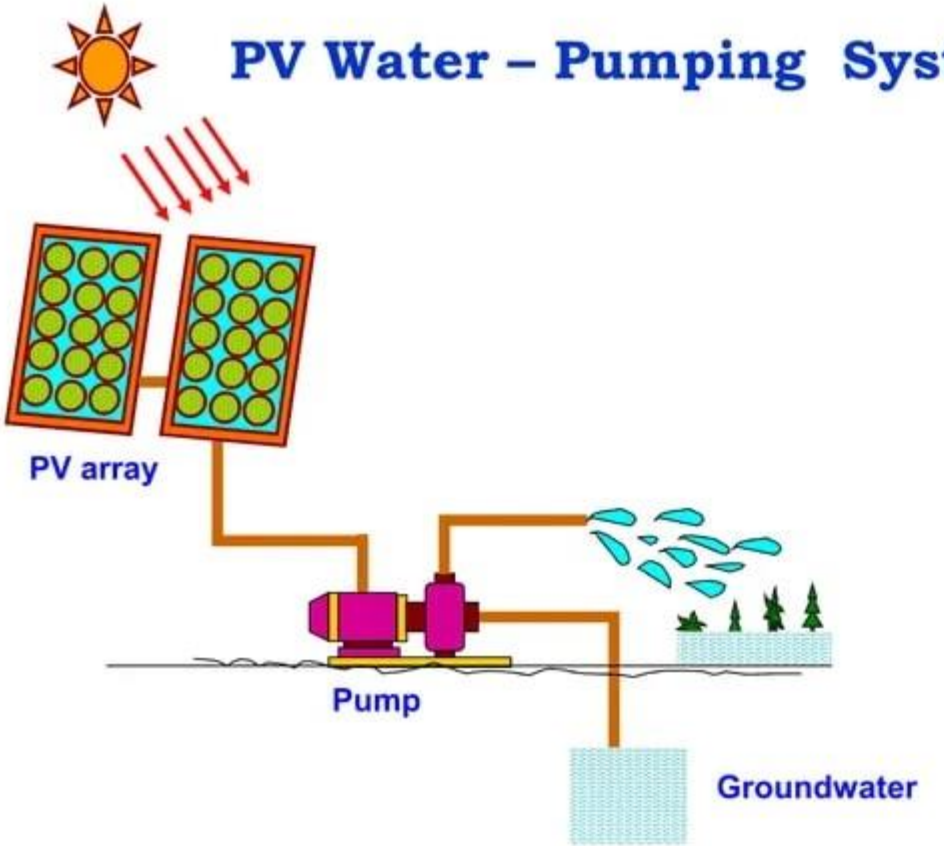


Key components of a solar home system

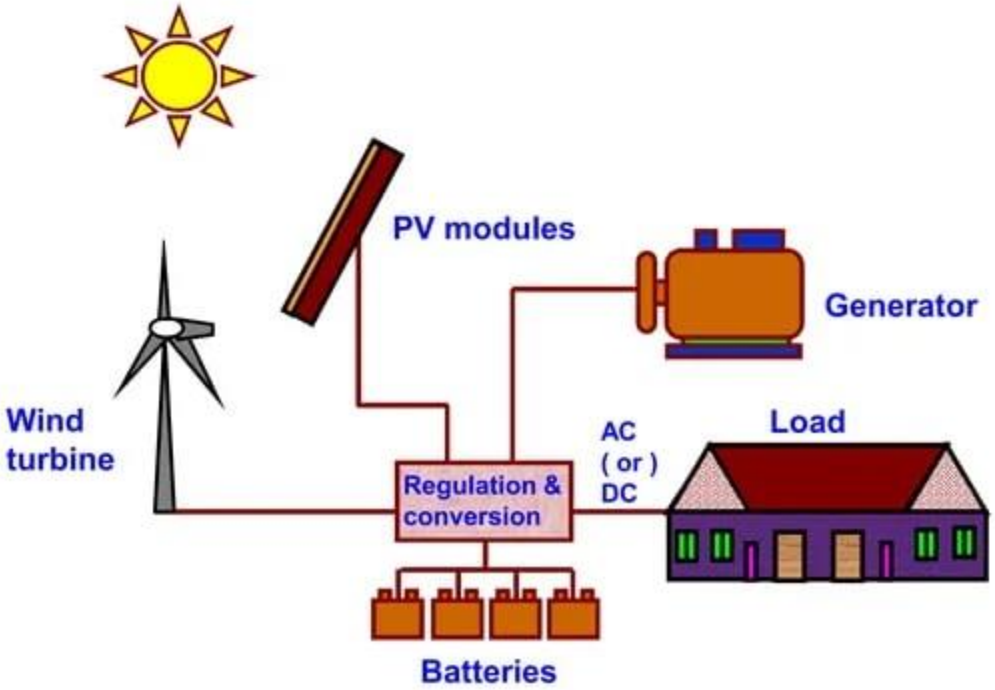


Key Components of a solar Street Lighting System

PV Water – Pumping System



PV Hybrid System



APPLICATIONS

- Remote Residential
- Village Power
- Stand Alone Systems
- Building-Integrated PV(BIPV)
- Consumer Product Power
- Hybrid Power System
- Space Power System

L A N T E R N

HOME LIGHTING

STREET LIGHTING

WATER PUMPING

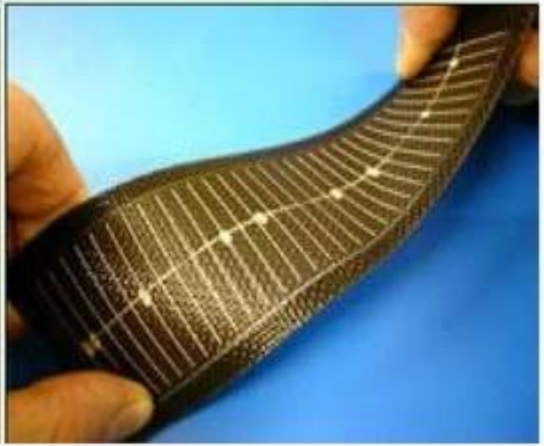
POWER PLANT

IN TRAFFIC

RAILWAY STATION

PV TILES

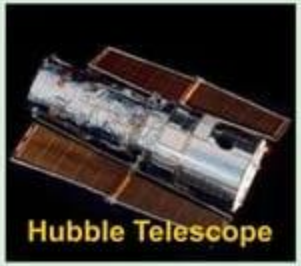

FLEXIBLE PV CELL



Remote Areas (Mexico)

A solar panel in Marla, Cirque de Mafate, Réunion

Spacecraft



Recreational Use (Sailboat)

Residential

Commercial

Solar Centre at Baglan Energy Park in South Wales

Architectural integration of PV modules on exterior walls