PARVATHAREDDY BABUL REDDY

VISVODAYA INSTITUTE OF TECHNOLOGY & SCIENCE

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INTRODUCTION

TO

PV ENERGY SYSTEM

UNIT-II

CLASS-IV-I SEM

Subject: RENEWABLE ENERGY SYSTEMS

SYLLABUS

UNIT-II-----------> PV ENERGY SYSTEMS

- Introduction, The PV effect in crystalline silicon basic principles, the film PV, Other PV technologies, Electrical characteristics of silicon PV cells and modules, PV systems for remote power, Grid connected PV systems.

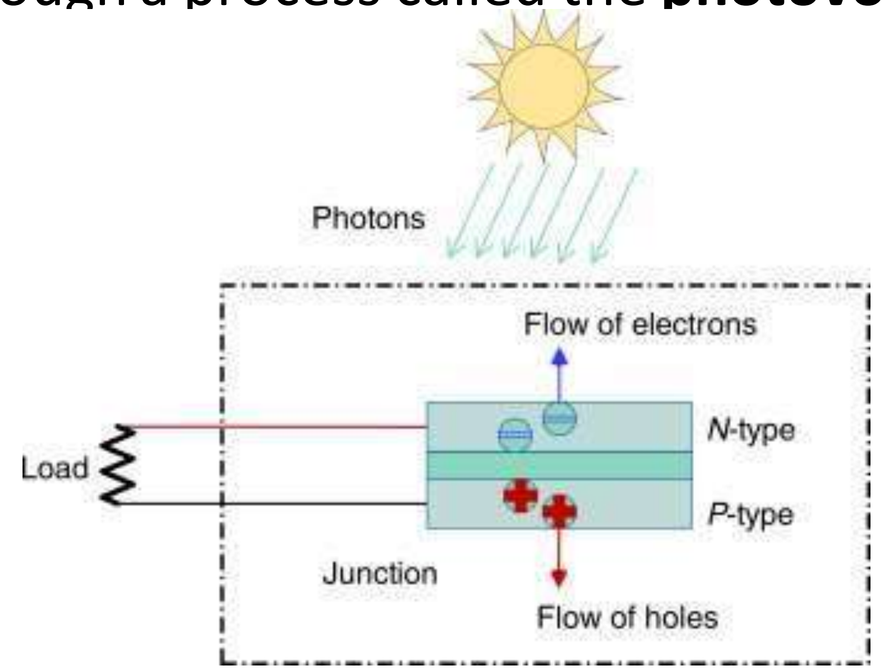
PHOTOVOLTAIC SYSTEM

- A photovoltaic (PV) system is composed of one or more solar panels combined with an inverter and other electrical and mechanical hardware that use energy from the Sun to generate electricity.
- PV systems can vary greatly in size from small roof top or portable systems to large-scale generation plants.

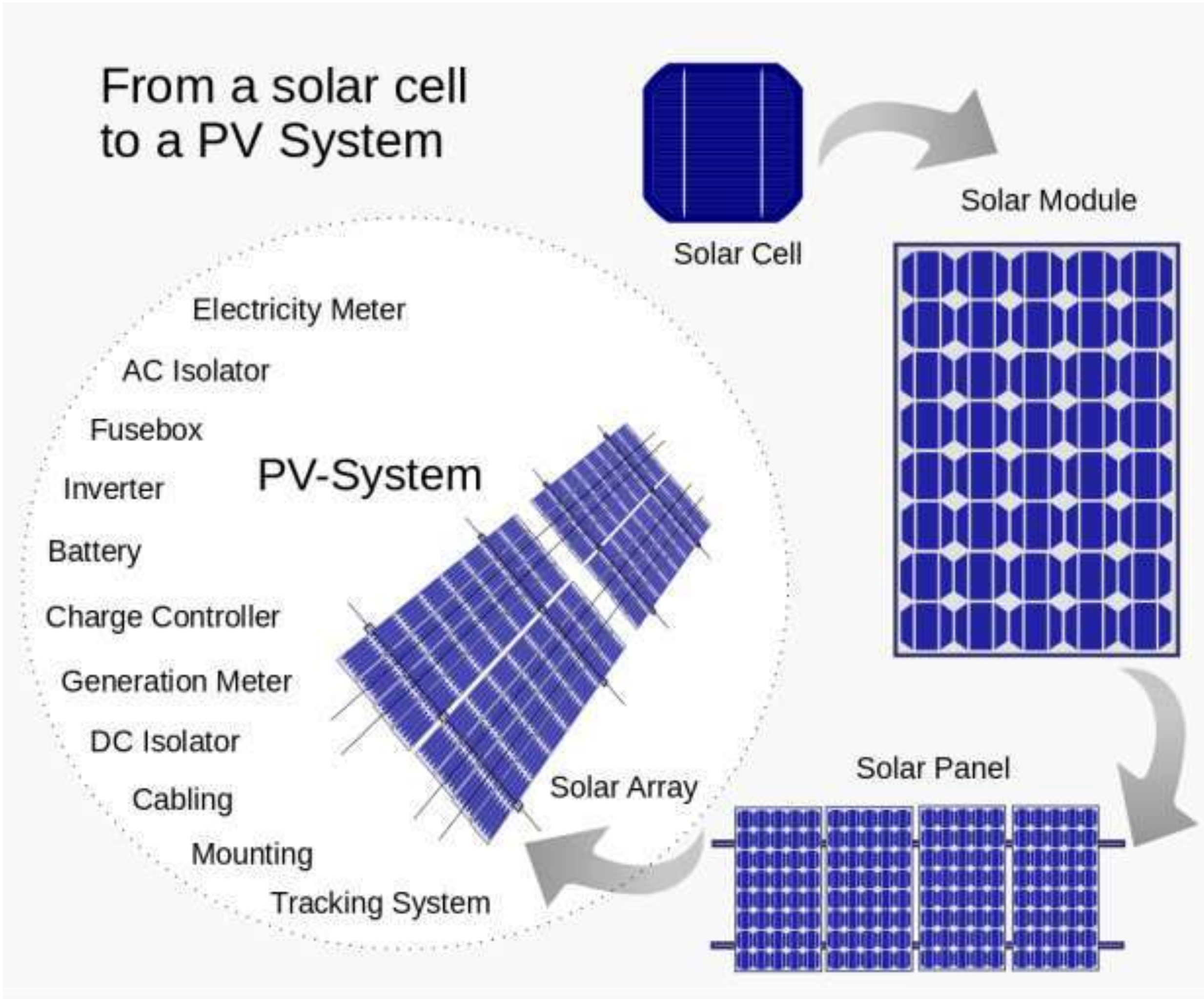
SOLAR PV SYSTEM

PHOTOVOLTAIC EFFECT

- The light from the Sun, made up of packets of energy called photons, falls onto a solar panel and creates an electric current through a process called the **photovoltaic effect**.



PHOTOVOLTAIC SYSTEM



INVERTER

- The electricity produced from a solar panel (or array) is in the form of direct current (DC).
- Therefore, in order for the solar electricity to be useful it must first be converted from DC to AC using an **inverter**.
- This AC electricity from the inverter can be used to power electronics locally, or be sent on to the electrical grid for use elsewhere.

RACKING

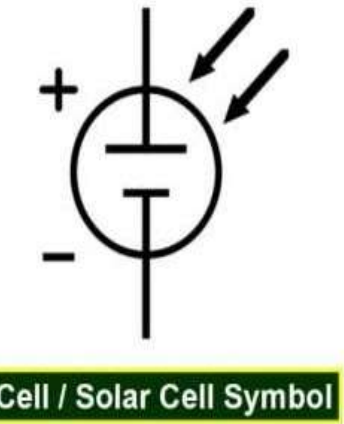
- Racking refers to the mounting apparatus which fixes the solar array to the ground or rooftop.
- Typically constructed from steel or aluminum, these apparatuses mechanically fix the solar panels in place with a high level of precision.
- Racking systems should be designed to withstand extreme weather events such as hurricane or tornado level wind speeds

Other Components

- The remaining components of a typical solar PV system include combiners, disconnects, breakers, meters and wiring.

WHAT IS A PV CELL OR SOLAR CELL?

- A PV Cell or Solar Cell or Photovoltaic Cell is the smallest and basic building block of a Photovoltaic System .
- These cells vary in size ranging from about 0.5 inches to 4 inches.



- These are made up of solar photovoltaic material that converts solar radiation into direct current (DC) electricity.

MATERIALS USED FOR PHOTOVOLTAIC CELL

- Mono crystalline Silicon,
- Polycrystalline Silicon,
- Microcrystalline Silicon,
- Cadmium Telluride, And
- Copper Indium Selenide /Sulfide.

COMPONENTS OF SOLAR CELL

The solar cell consists of

(i) p-type silicon material layer,

(ii) n-type silicon material layer,

(iii) Front metallic grid and

(iv) Opaque back metal contact as shown in Figure

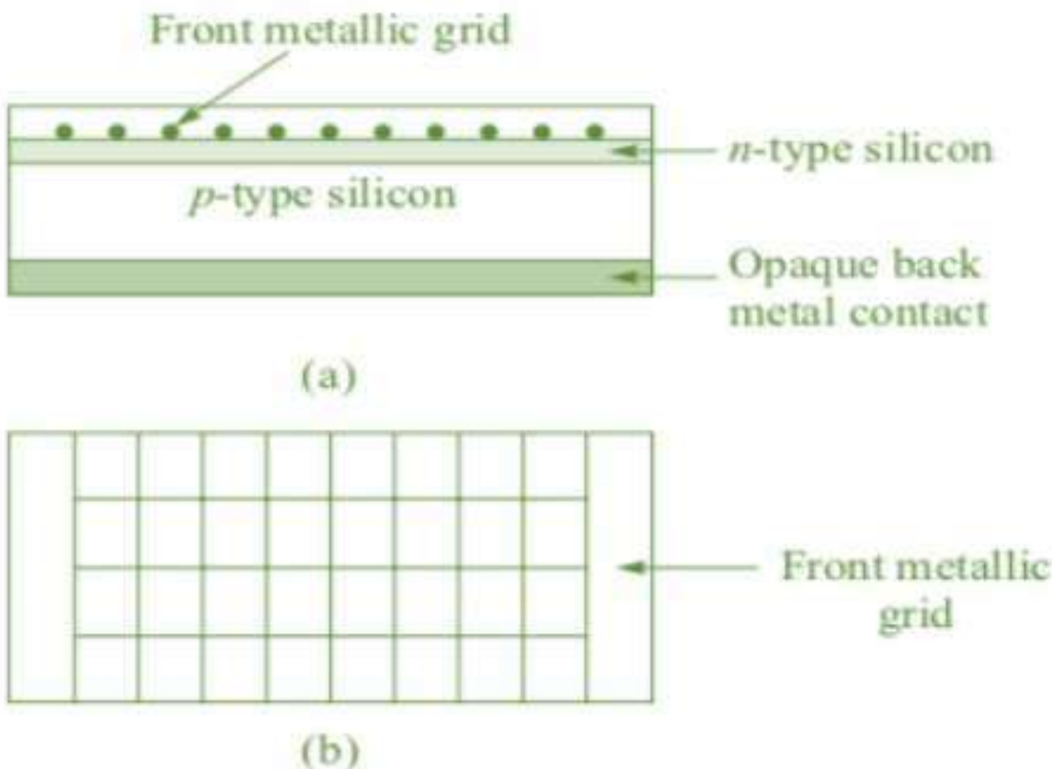


Figure 3.24 Construction of a solar cell. (a) Side view of the solar cell. (b) Top view of the solar cell.

CONSTRUCTION DETAILS

- The bulk material consists of p-type silicon having thickness about 100-350 mm.

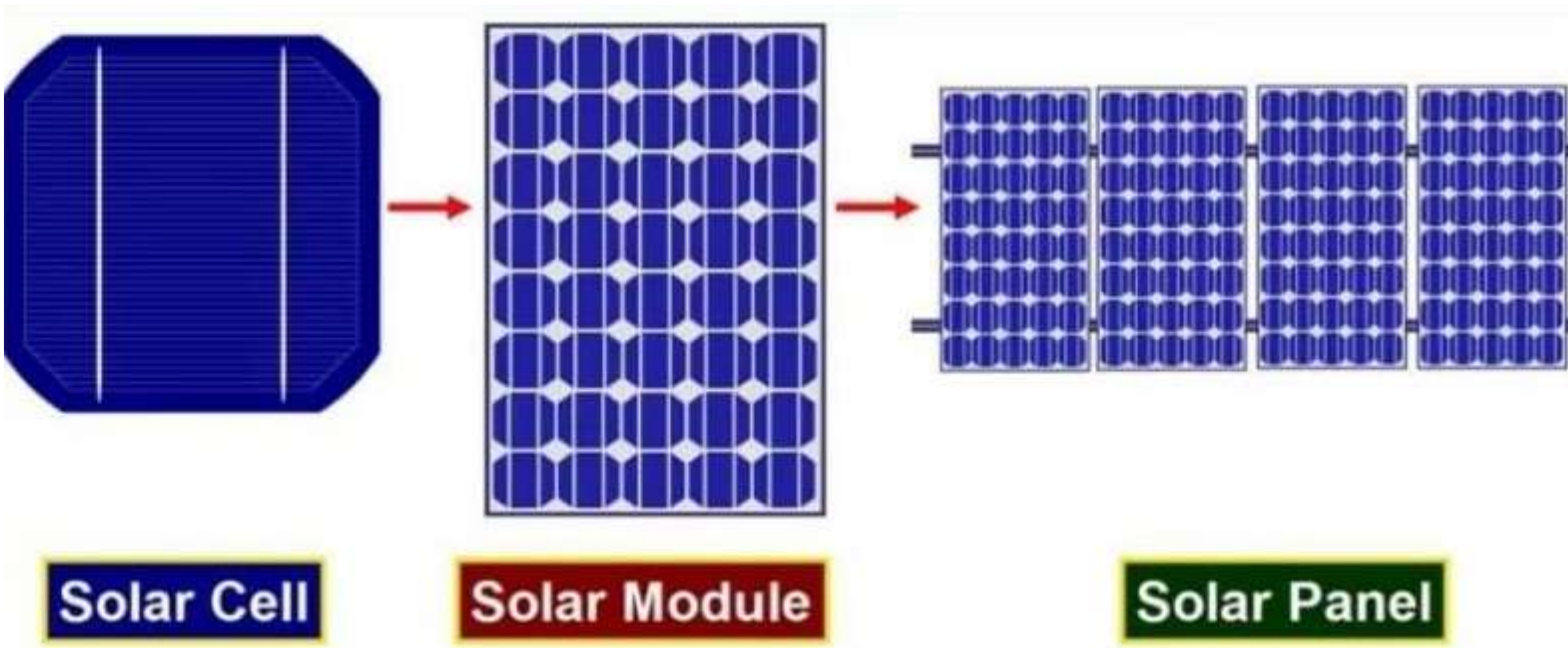
- A thin layer of n-type silicon having thickness of about 2 mm is diffused on this bulk material, providing p-n junction.

- A metallic grid at top with n-type material and an opaque back metal contact at the bottom of p-type material are provided which also act as negative and positive terminals.

SOLAR PHOTOVOLTAIC PANELS

- An array or Solar PV Cells are electrically connected together to form a PV Module and an Array of such Modules are again electrically connected together to form a Solar Panel.
- This connection is done by soldering using flux cored solder wire and PV Ribbon.

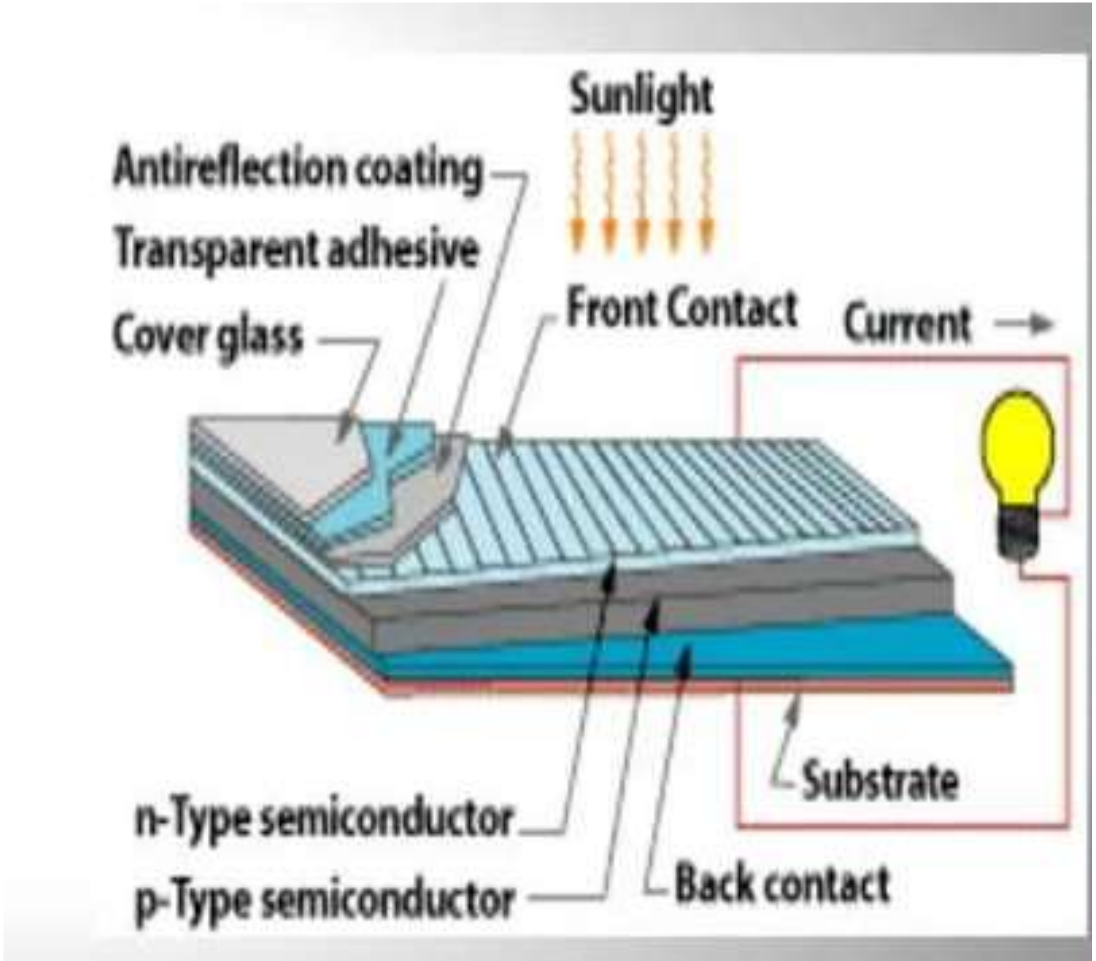
SOLAR CELL, SOLAR MODULE AND SOLAR PANEL



PV CELL WORKING PRINCIPLE TO GENERATE ELECTRICITY

- Solar cells convert the energy in sunlight to electrical energy.
- Solar cells contain a material such as silicon that absorbs light energy.
- The energy knocks electrons loose so they can flow freely and produce a difference in electric potential energy, or voltage.

Layers of a PV Cell



Layers of a PV Cell

- A photovoltaic cell is comprised of many layers of materials, each with a specific purpose.
- The most important layer of a photovoltaic cell is the specially treated semiconductor layer.
- It is comprised of two distinct layers of p-type and n-type, and is what actually converts the Sun's energy into useful electricity through a process called the photovoltaic effect.
- On either side of the semiconductor is a layer of conducting material which "collects" the electricity produced.

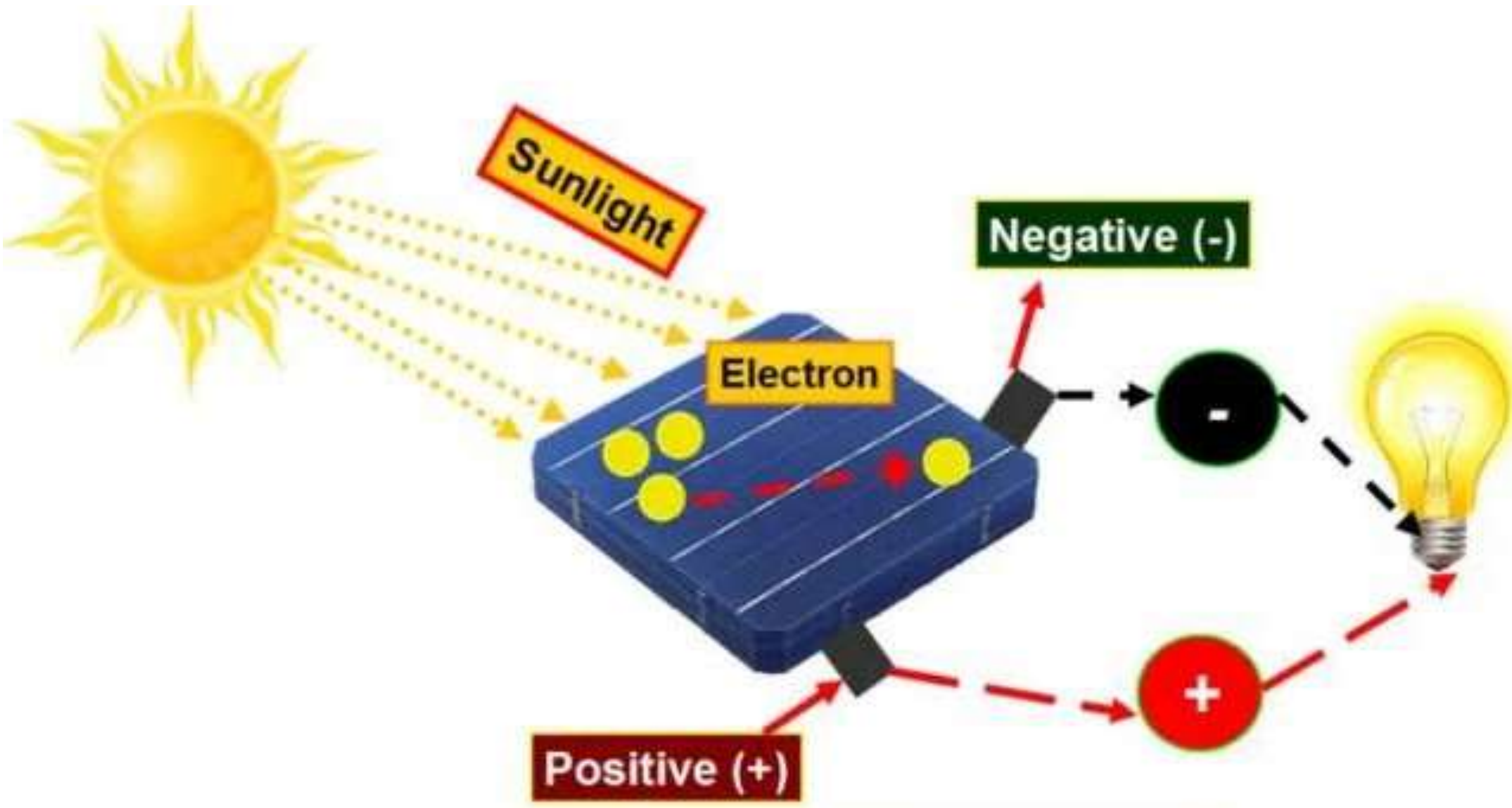
Layers of a PV Cell

- Note that the backside or shaded side of the cell can afford to be completely covered in the conductor, whereas the front or illuminated side must use the conductors sparingly to avoid blocking too much of the Sun's radiation from reaching the semiconductor.
- The final layer which is applied only to the illuminated side of the cell is the anti-reflection coating.
- Since all semiconductors are naturally reflective, reflection loss can be significant.
- The solution is to use one or several layers of an anti-reflection coating (similar to those used for eyeglasses and cameras) to reduce the amount of solar radiation that is reflected off the surface of the cell.

PV CELL WORKING PRINCIPLE TO GENERATE ELECTRICITY

- The flow of electrons or negative charge creates electric current.
- Solar cells have positive and negative contacts, like the terminals in a Battery.
- If the contacts are connected with a conductive wire, current flows from the negative to positive contact.
- The Figure below shows how a PV cell works to generate electricity.

PV CELL WORKING PRINCIPLE TO GENERATE ELECTRICITY



TYPES OF SOLAR CELL

- There are different types of photovoltaic cells available to buy, but mainly they are manufactured from silicon (Si).
- The use of silicon in the manufacture of photovoltaic cells produces the stereo typical uniform blue coloured PV cell which we see on roof tops and the sides of buildings.
- The two major types of photovoltaic cell materials used are crystalline silicon and thin film deposits, which vary from each other in terms of light absorption efficiency, energy conversion efficiency, manufacturing technology and cost of production.

TYPES OF SOLAR CELL

- Crystalline silicon PV cells are the most common type of photovoltaic cell in use today and are also one of the earliest successful PV devices.
- The three general types of photovoltaic cells made from silicon are:

1. Mono-crystalline Silicon – also known as single-crystal silicon
2. Poly-crystalline Silicon – also known as multi-crystal silicon
3. Thin Film Silicon

Crystalline Silicon (c-Si)

- This is the most common technology used to produce photovoltaic cells representing about 90% of the market today.
- Crystalline photovoltaic cells are made from silicon which is first melted, and then crystallised into ingots or casting's 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%.

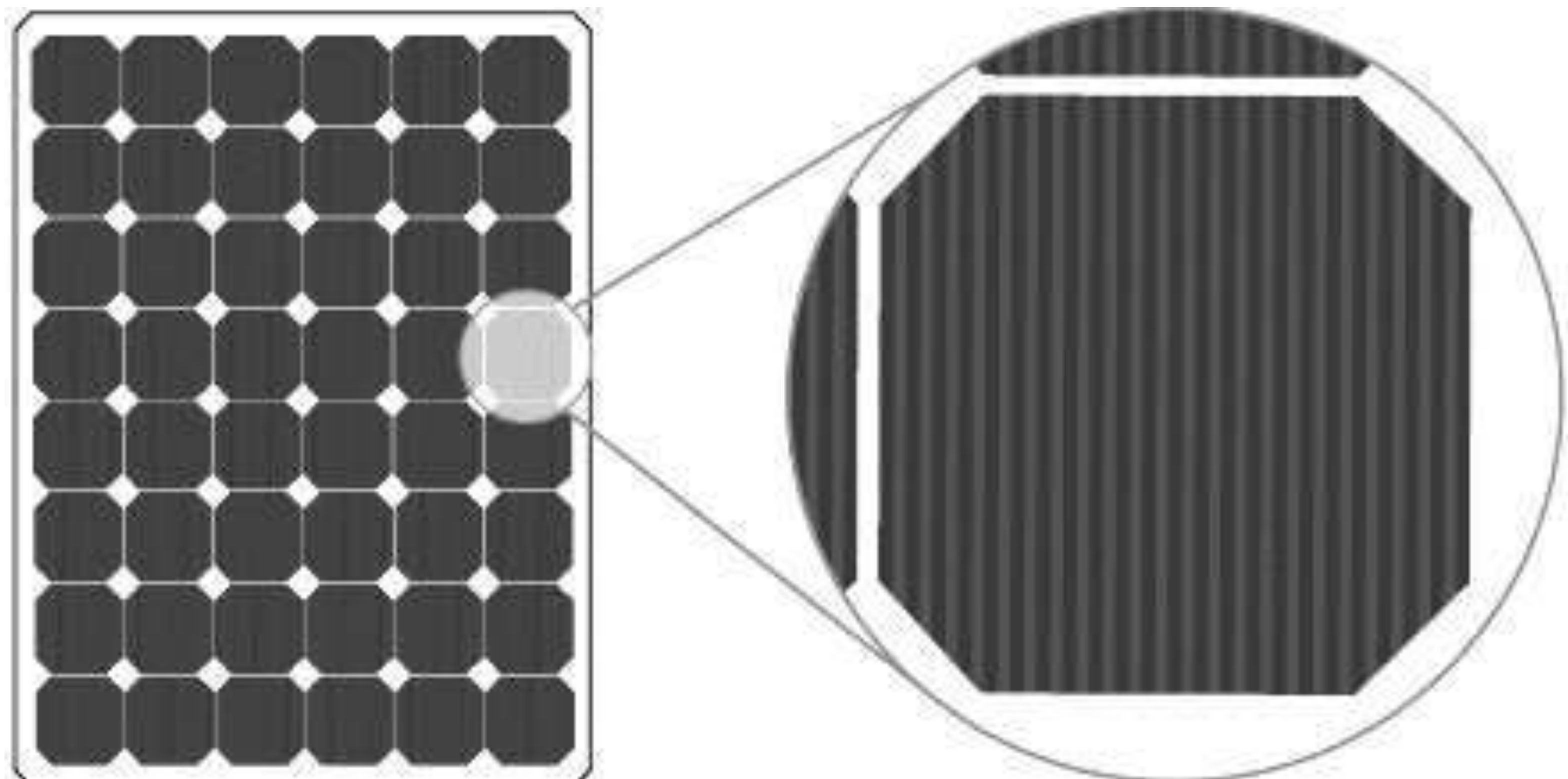
Mono-crystalline

- Silicon is a type of photovoltaic cell material manufactured from a single-crystal silicon structure which is uniform in shape because the entire structure is grown from the same crystal.
- High purity silicon is melted in a crucible. A single-crystal silicon seed is dipped into this molten silicon and is slowly pulled out from the liquid producing a single-crystal ingot.
- The ingot is then cut into very thin wafers or slices which are then polished, doped, coated, interconnected and assembled into modules and arrays.
- These types of photovoltaic cells are also widely used in photovoltaic panel construction.

Mono-crystalline

- Compared to non-crystalline cells, the uniform molecular structure of the silicon wafer makes it ideal for transferring loose electrons through the material resulting in a high energy conversion efficiency.
- The conversion efficiency for a mono-crystalline cell ranges between 15 to 20%.
- Not only are they energy efficient, mono-crystalline photovoltaic cells are highly reliable for outdoor power applications due to their wafer thickness.
- However, to make an effective PV cell, the silicon has to be —doped‖ with other elements to make the required N-type and P-type conductive layers.

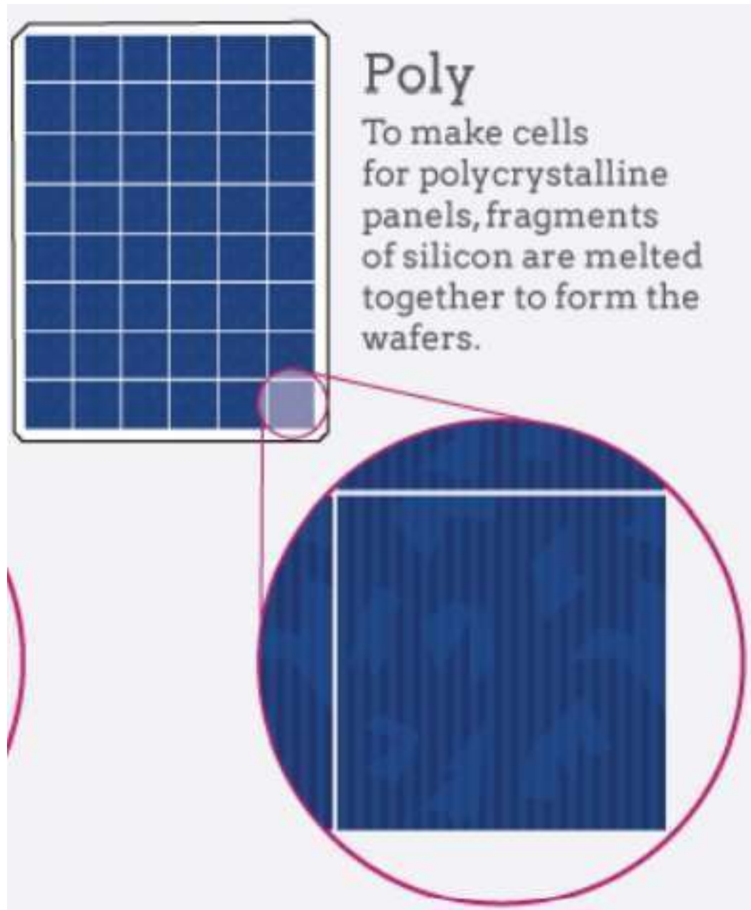
Monocrystalline solar panels



Poly-crystalline solar panels

- Silicon also known as multi-crystalline silicon, is cast to produce a silicon ingot.
- The silicon molecular structure consists of several smaller groups or grains of crystals, which introduce boundaries between them.
- Poly-crystalline PV cells are less energy efficient than the previous mono-crystalline silicon PV cells because these boundaries restrict the flow of electrons through it by encouraging the negative electrons to recombine with the positive holes reducing the power output of the cell.
- The result of this means that a poly-crystalline PV cell only has an energy conversion efficiency of between 10 to 14%.
- However, these types of photovoltaic cell are much less expensive to produce than the equivalent single mono-crystalline silicon due to their lower manufacturing costs.

Poly-crystalline solar panels



THIN-FILM SOLAR CELLS

- Thin-film solar cells are made by depositing one or more thin layers (thin films or TFs) of photovoltaic material onto a substrate, such as glass, plastic or metal.

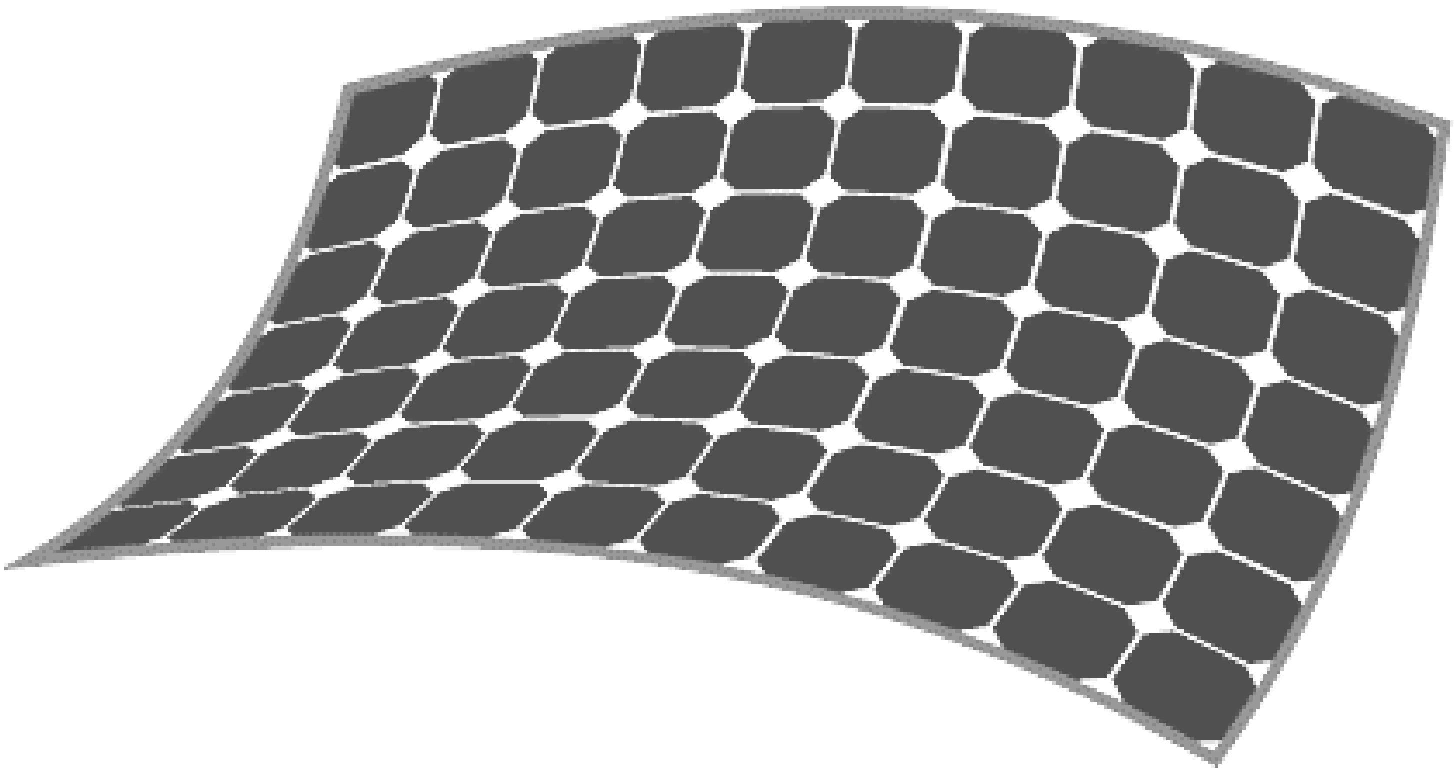
Thin Film Solar Cell

- Thin Film Solar Cells are another type of photovoltaic cell which were originally developed for space applications with a better power-to-size and weight ratio compared to the previous crystalline silicon devices.
- 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.

Thin Film Solar Cell

- 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: Cadmium Telluride, Amorphous Silicon and Copper Indium diSelenide or CIS.

Thin Film Solar Cell



Cadmium Telluride, (CdTe)

- **Cadmium Telluride, (CdTe) is a poly-crystalline semiconductor material made from cadmium and tellurium.**
- **Thin film cadmium telluride has a high light absorption level so the amount of CdTe required can be quite minimal with less than 1.0 microns of semiconductor material is needed to effectively absorb sunlight for the solar device to perform.**
- Although the process of spraying or printing the thin film is relatively easy making it cheap to manufacture these types of photovoltaic cell, the main material, cadmium is a toxic heavy metal can pollute the environment if the cell is damaged or broken.
- Another disadvantage of these types of photovoltaic cells is that the conversion efficiency for a cadmium telluride PV cell can be low at less than 10%.

Amorphous Silicon, (a-Si)

- Amorphous Silicon, (a-Si) is a non-crystalline form of silicon that is widely used in calculators, consumer electronics and solar garden products that require a small current at a low voltage.
- 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.

Amorphous Silicon, (a-Si)

- 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, two of the main disadvantages of amorphous silicon (a-Si) is its very low conversion efficiency ranging from between 7 to 9% when new, degrading down within a few months of exposure to sunlight to less than 5%.

Copper Indium diSelenide, (CIS)

- **Copper Indium diSelenide, (CIS) is another type of poly-crystalline semiconductor material composed of Copper, Indium and Selenium, ($CuInSe_2$).**
- **Thin film CIS types of photovoltaic cell can produce conversion efficiencies of nearly 10%, almost double that of amorphous silicon without suffering from the same outdoor degradation problems due to their thicker film.**

- **Also CIS cells are one of the most light-absorbent semiconductor compounds absorbing up to 90% of the solar spectrum.**
- Although Copper Indium diSelenide, CIS cells are efficient, the complexity of the formulation of the semiconductor compound makes them difficult to manufacture and expensive.
- Also, Indium is a relatively expensive material due to its limited availability with manufacturing safety issues a concern as hydrogen selenide is an extremely toxic gas.

Copper Indium Gallium diSelenide, (CIGS)

- Copper Indium Gallium diSelenide, (CIGS) is another type of photovoltaic cell.
- It is basically a P-type poly-crystalline thin film material based on the previous copper indium diselenide (CIS) semiconductor material.
- The addition of small amounts of the compound Gallium (Ga) produces a photovoltaic cell with a higher conversion efficiency of around 12% from the same amount of sunlight with an open circuit voltage of about 0.7 volts.
- This is because Gallium, which is a liquid similar to mercury at room temperatures, increases the light-absorbing band gap of the cell, which matches more closely the solar spectrum, thereby improving its conductivity allowing electrons to freely move through the cell to the electrodes.

Other Types of Photovoltaic Cell

- Apart from the commonly used types of photovoltaic cell mentioned above, and which account for about 95% of the commercial market, other types of photovoltaic cell currently being developed include:
- **Multijunction PV Cells**
- **Dye-Sensitive PV Cells**
- **3D Photovoltaic Cells**

Multi junction PV Cells

- **These are types of photovoltaic cell designed to maximise 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.

Multi junction PV Cells

- 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.

Dye-Sensitive PV Cells

- – This type of technology is considered to be the 3rd generation of solar cells.
- Instead of using solid-state PN-junction technology to convert photon energy into electrical energy, an electrolyte, 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.
- The photon light energy being absorbed by the dye releases electrons into the conduction band causing a flow of the electricity through the semiconductor.
- The advantage of a dye-sensitive nano-crystalline photo-electrochemical photovoltaic cell is that the dye can be screen printed onto any surface producing conversion efficiencies of around 10%.

3D Photovoltaic Cells

- – This type of 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.

Comparison of types of Solar cells

Solar panel type	Advantages	Disadvantages
Monocrystalline	• High efficiency/performance • Aesthetics	• Higher costs
Polycrystalline	• Low cost	• Lower efficiency/performance
Thin-film	• Portable and flexible • Lightweight • Aesthetics	• Lowest efficiency/performance

Table: Comparison of types of Solar cells

Comparison of Types of solar cell

Material	*Efficiency (%)*
Monocrystalline silicon	14-17
Polycrystalline silicon	13-15
Amorphous silicon	5-7

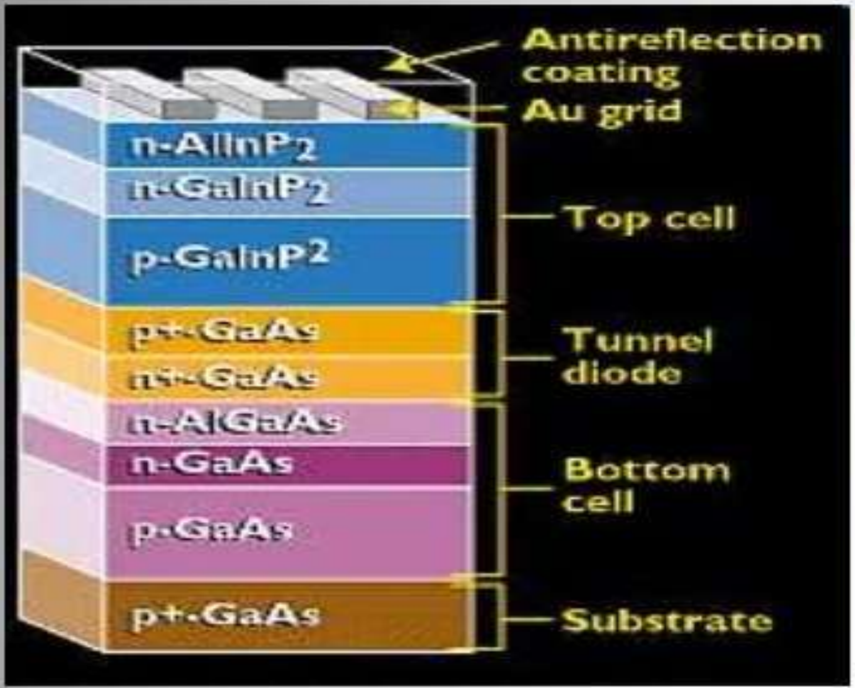
TYPES OF SOLAR CELL

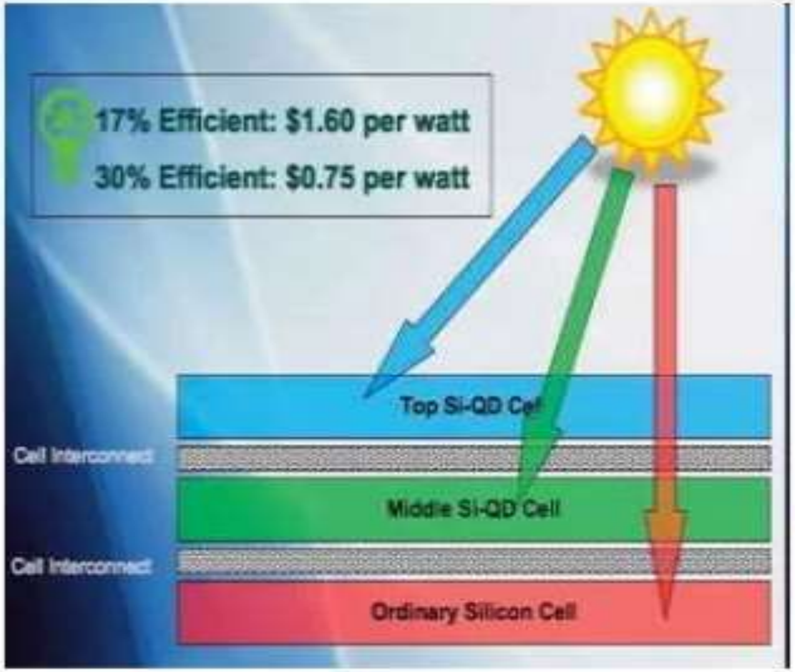
1st Generation Solar Cells

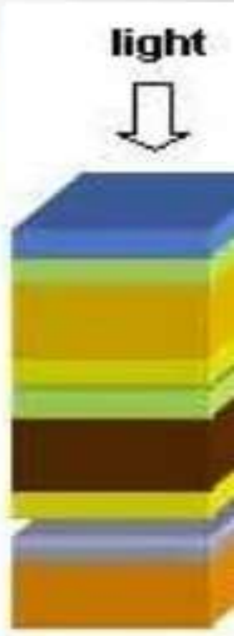
2nd Generation Solar Cells

3rd Generation Solar Cells

Third Generation – Multi-junction Cells







➢Enhance poor electrical performance while maintaining v
costs.

➢Current research is targeting conversion efficiencies

Advantages of solar cell

- It is clean and non-polluting.
- It is a renewable energy.
- Solar cells do not produce noise and they are totally silent.
- They require very little maintenance.
- They have long life time.
- There are no fuel costs or fuel supply problems.

Disadvantages of solar cell

- Soar cells (or) solar panels are very expensive.
- Air pollution and whether can affect the production of electricity.
- They need large are of land to produce more efficient power supply.
- Sun does not shine consistently.
- Less efficient and costly equipment.
- Reliability Depends On Location

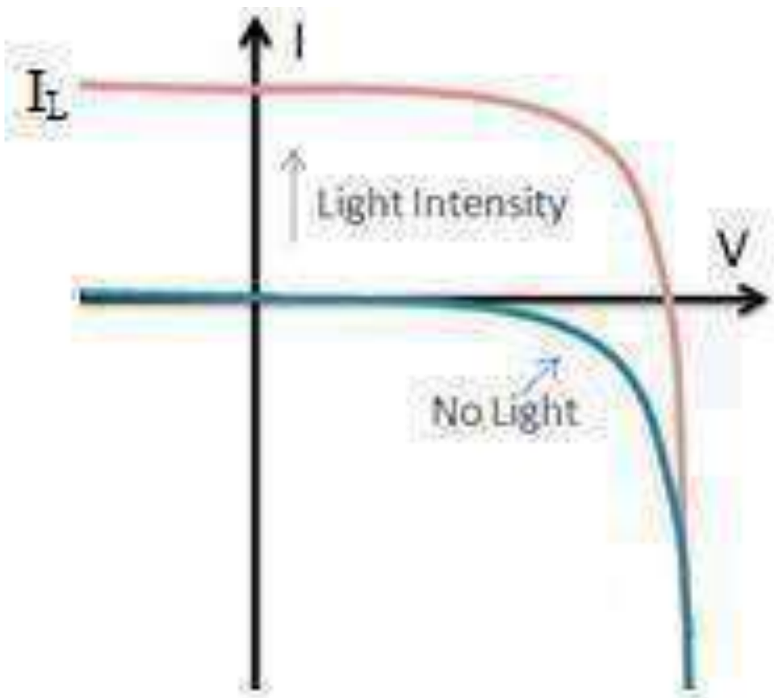
Applications of solar energy

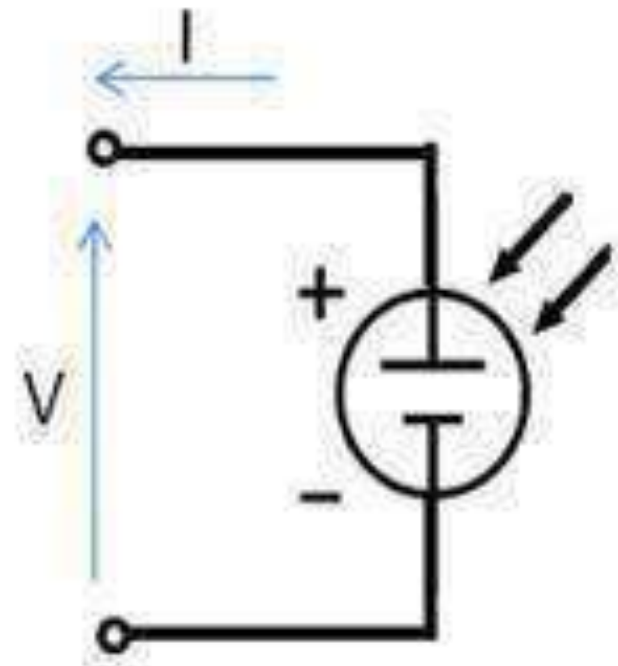
- Domestic power supply.
- Electric power generation in space.
- Drying Agricultural Products.
- Solar pumps are used for water supply.
- Water Heating.
- Generating Electrical Power.
- To providing electrical power to satellites.

Electrical characteristics of silicon PV cells and modules

- PV cells can be modeled as a current source in parallel with a diode.
- When there is no light present to generate any current, the PV cell behaves like a diode.
- As the intensity of incident light increases, current is generated by the PV cell, as illustrated in Figure.

Electrical characteristics of silicon PV cells and modules





Electrical characteristics of silicon PV cells and modules

- In an ideal cell, the total current I *is equal to the current* I_ℓ generated by the photoelectric effect minus the diode current I_D,
- *according to the equation:*

$$I = I_\ell - I_D$$

$$I = I_L - I_D = I_L - I_o\left(e^{\frac{qV}{kT}} - 1\right)$$

- where

  I_0 is the saturation current of the diode

  q is the elementary charge 1.6x10-19 Coulombs,

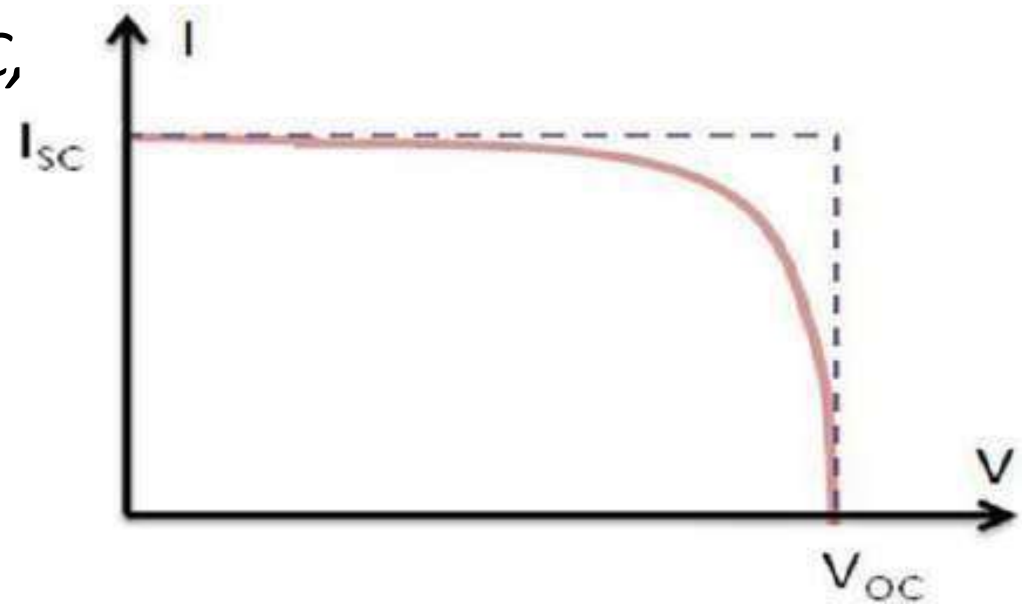
  k is a constant of value 1.38x10-23J/K

  T is the cell temperature in Kelvin

  V is the measured cell voltage that is either produced

I-V curve of a PV cell

- The I-V curve of an illuminated PV cell has the shape shown in the following Figure as the voltage across the measuring load is swept from zero to *VOC*,



Short Circuit Current (ISC)

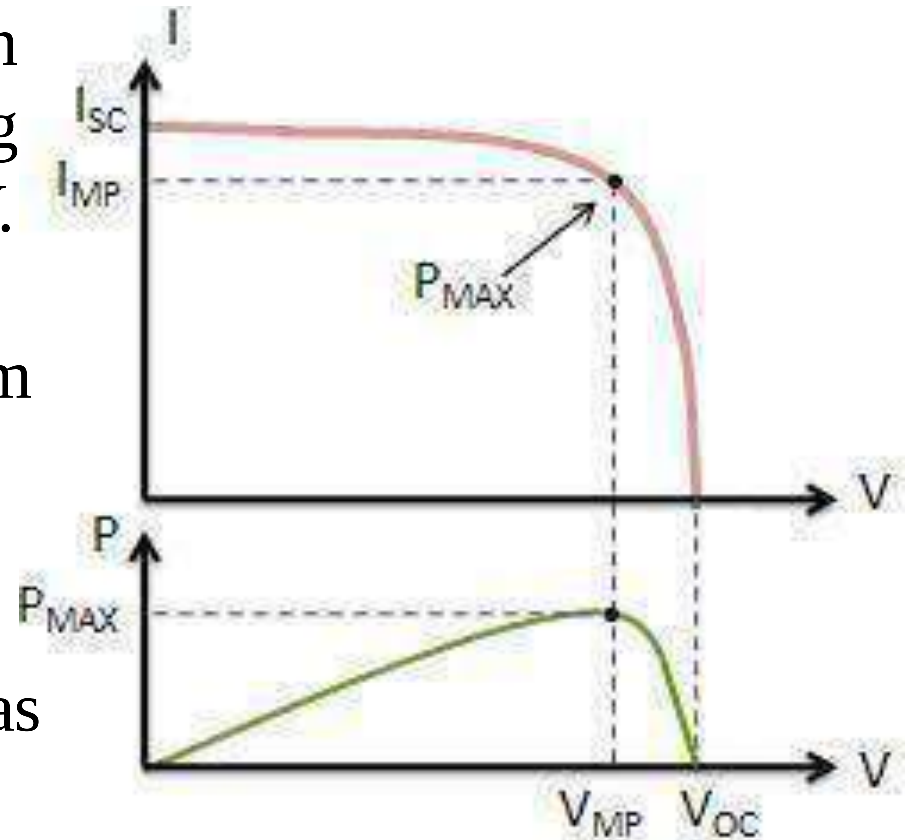
- The short circuit current ISC corresponds to the short circuit condition
- when the impedance is low and is calculated when the voltage equals 0.
- I (at V=0) = ISC
- ISC occurs at the beginning of the forward-bias sweep and is the maximum current value in the power quadrant.
- For an ideal cell, this maximum current value is the total current produced in the solar cell by photon excitation.
- ISC = IMAX = Iℓ for forward-bias power quadrant

Open Circuit Voltage (VOC)

- The open circuit voltage (V_{OC}) occurs when there is no current passing through the cell.
- V (at I=0) = V_{OC}
- V_{OC} is also the maximum voltage difference across the cell for a forwardbias sweep in the power quadrant.
- V_{OC}= V_{MAX} for forward-bias power quadrant

Maximum Power (PMAX), Current at PMAX (IMP), Voltage at PMAX (VMP)

- The power produced by the cell in Watts can be easily calculated along the I-V sweep by the equation *P=IV*.
- *At the ISC and VOC points, the power* will be zero and the maximum value for power will occur between the two.
- The voltage and current at this maximum power point are denoted as *VMP and IMP respectively.*

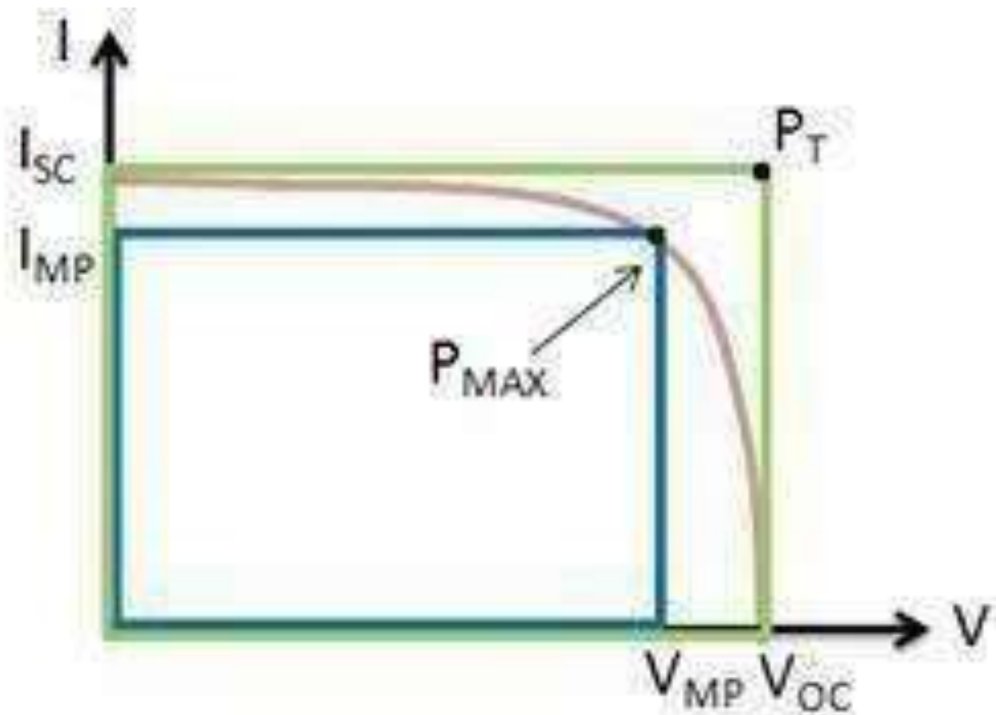


Fill Factor

- The Fill Factor (FF) is essentially a measure of quality of the solar cell.
- It is calculated by comparing the maximum power to the theoretical power (P_T) *that would be output at both the open circuit voltage and short* circuit current together.
- FF can also be interpreted graphically as the ratio of the rectangular areas depicted in Figure

Fill Factor

$$FF = \frac{P_{MAX}}{P_T} = \frac{\boxed{I_{MP} \cdot V_{MP}}}{\boxed{I_{SC} \cdot V_{OC}}}$$



Fill Factor

- A larger fill factor is desirable, and corresponds to an I-V sweep that is more square-like.
- Typical fill factors range from 0.5 to 0.82. Fill factor is also often represented as a percentage.

Efficiency (η)

- Efficiency is the ratio of the electrical power output *Pout, compared to the* solar power input, *Pin, into the PV cell.*
- *Pout can be taken to be PMAX since* the solar cell can be operated up to its maximum power output to get the maximum efficiency.

$$\eta = \frac{P_{out}}{P_{in}} \Rightarrow \eta_{MAX} = \frac{P_{MAX}}{P_{in}}$$

Types of PV Systems

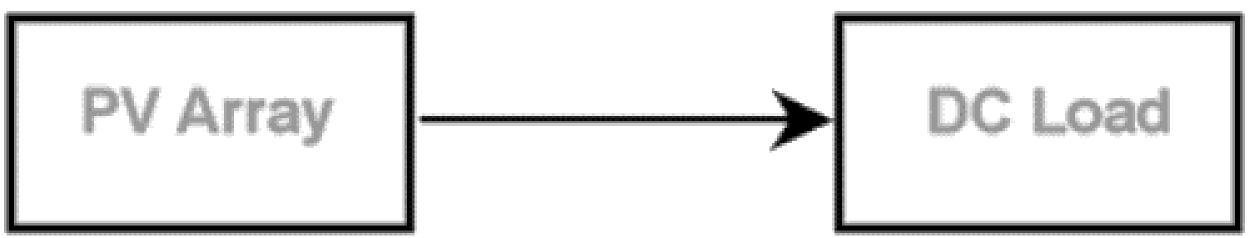
- Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads.
- The two principle classifications are grid-connected or utility-interactive systems and stand-alone systems.
- Photovoltaic systems can be designed to provide DC and/or AC power service, can operate interconnected with or independent of the utility grid, and can be connected with other energy sources and energy storage systems.

Types of PV Systems

- PV Direct System
- Solar Off Grid System
- Solar Grid Tied with Battery Backup System
- Hybrid system

PV Direct System

- These are the simple most type of solar PV systems, with the fewest components; the Solar Panels and the load.
- Because they don‘t have batteries and are not hooked up to the grid, they only power the loads when the sun is shining.
- They are appropriate for a few applications e.g. water pumping or Ventilation fan.



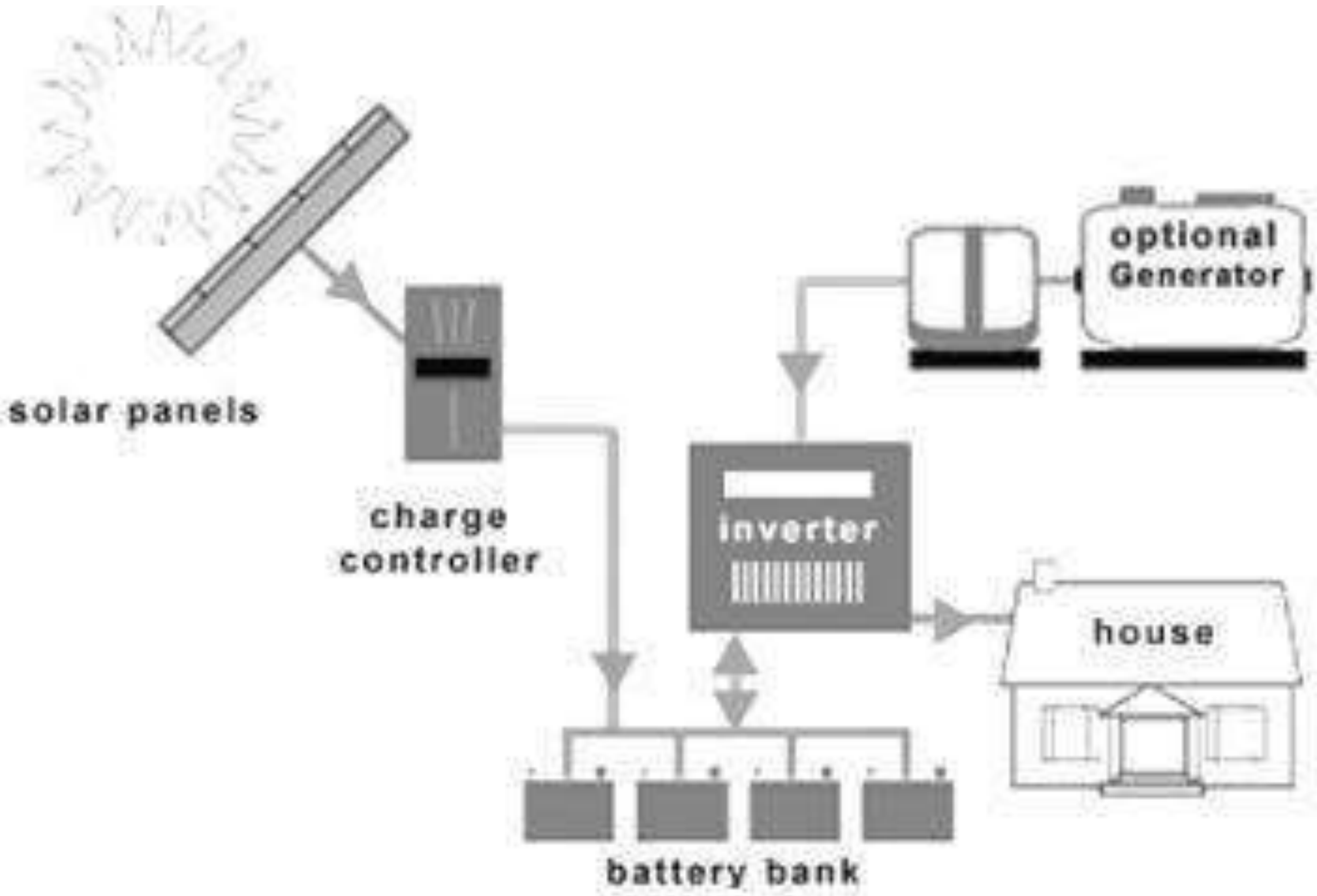
Solar Off Grid System

- Also referred to as stand-alone systems, it is designed to be independent of the power grid.
- Batteries are used to store energy when the sun is not available during cloudy days or at night.
- This type of system will require regular attention to battery electrolyte levels and terminal corrosion.

Solar Off Grid System

- Independence from the utility grid
- In remote areas, it is cost effective than extending a grid
- Batteries require maintenance and has limited life
- More components means more complexity
- Batteries decrease system efficiency
- It is more expensive than a grid-direct system
- When the batteries are fully charged, potential power from the PV array is not utilized
- If the PV system fails, back-up electricity is required to run load
- Most off-grid systems use a backup generator for non-sunny days. They are expensive, noisy, dirty, and require fuel and regular maintenance

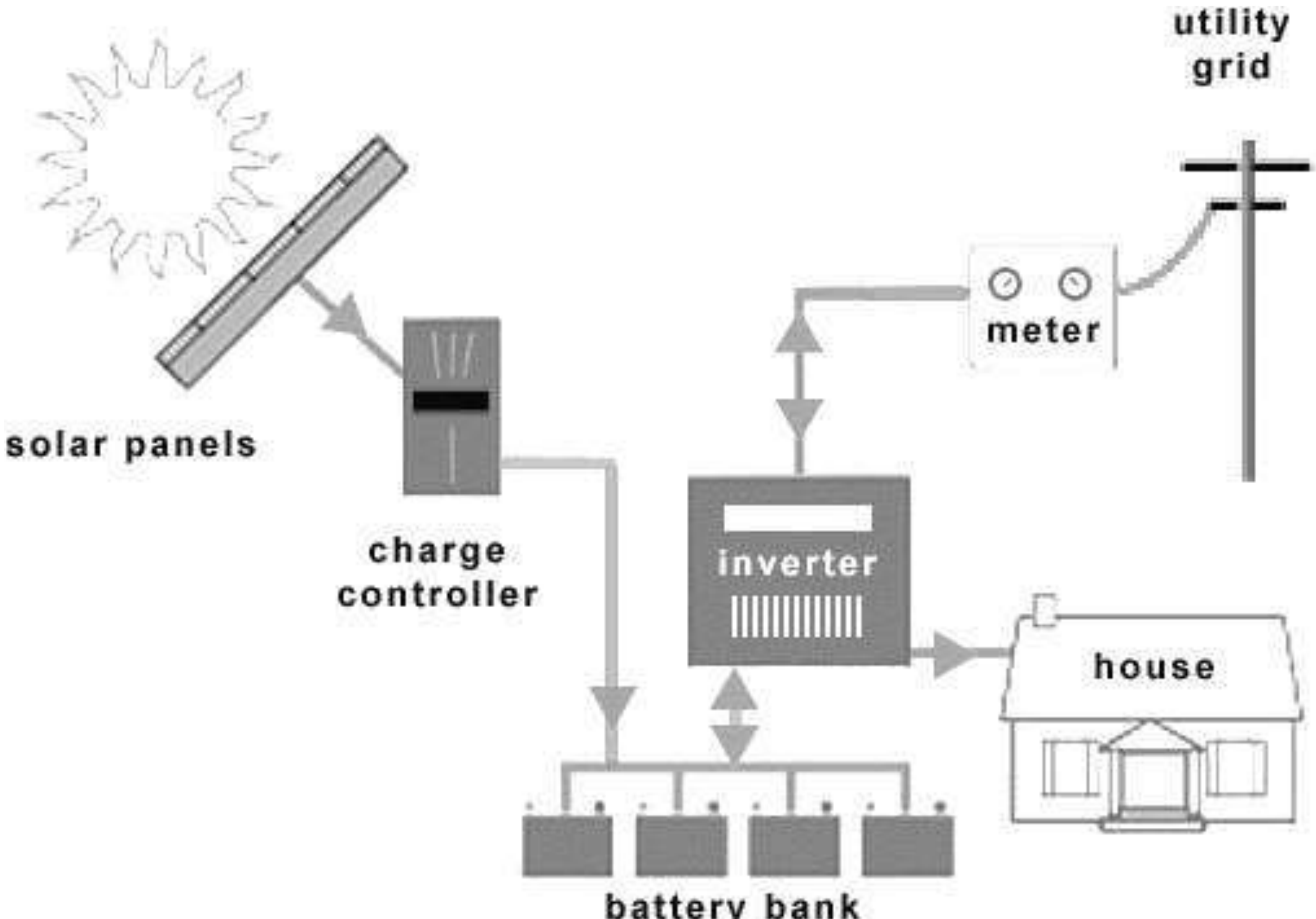
Solar Off Grid System



Solar Grid Tied with Battery Backup System

- This type is very similar to an off-grid system in design and components, but adds the utility grid, which reduces the need for the system to provide all the energy all the time.
- Grid-tied-with-battery-backup
- Designated loads have power when the grid goes down
- If the system produces more than the home needs, then the extra energy is sold back to the utility- not lost as in a stand-alone systems after the batteries get full on a sunny day

Gird tied solar system with battery back up



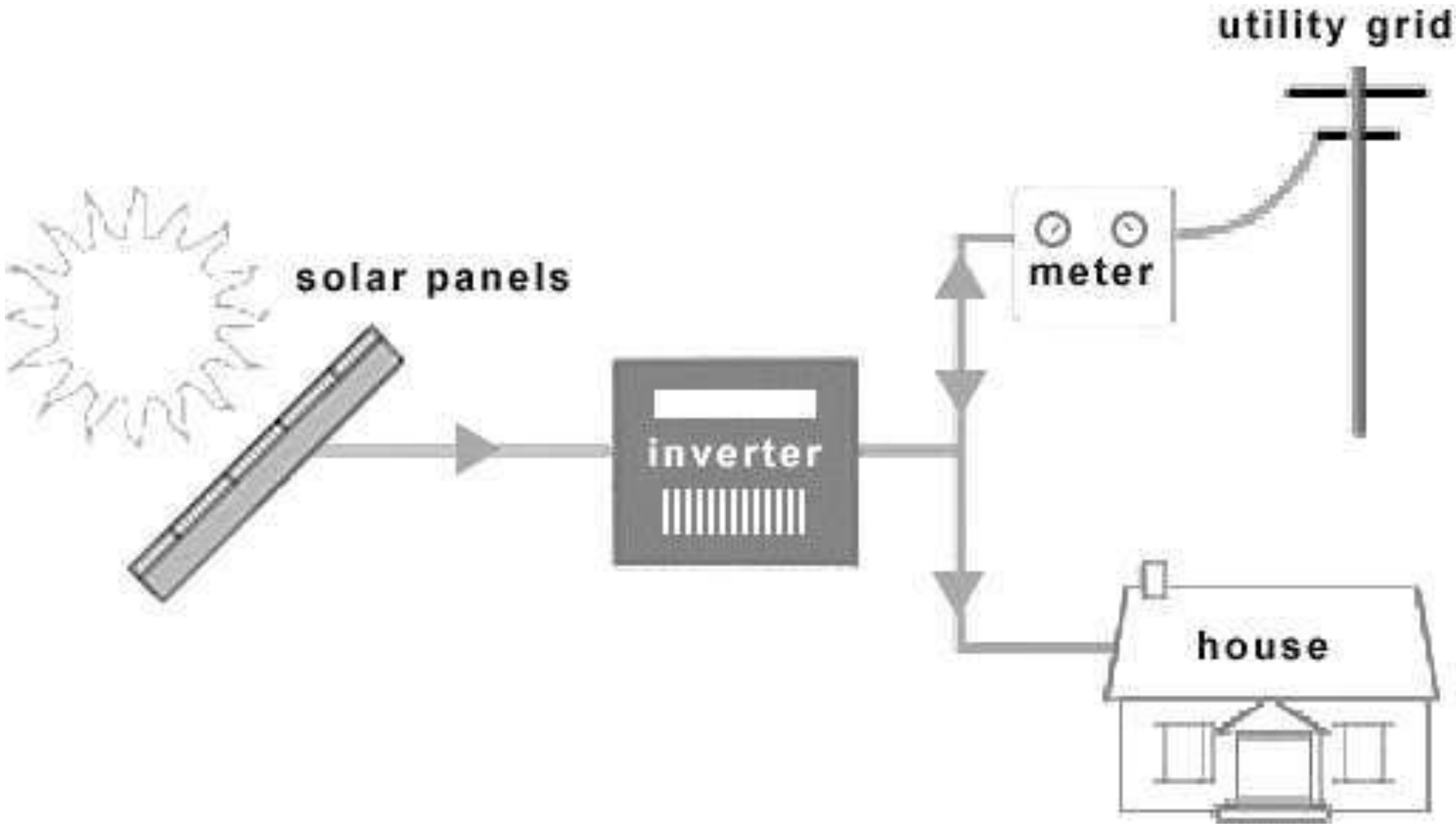
Gird tied solar system with battery back up

- Batteries require maintenance
- Requires rewiring circuits from main service panel to a separate subpanel
- More components mean more complexity
- Batteries decrease system performance because of their efficiency losses
- More expensive than a grid-direct system
- Typically only provides modest backup – usually not all of the loads are backed up.
- Requires paperwork for interconnection, incentives, and rebates

Solar Grid Tied System without Battery backup

- These are most common type of PV systems. They are also known as on-grid, grid-tied, grid-intertied, or grid-direct systems.
- They generate solar electricity and route it to the loads and to the grid, offsetting some of electricity usage.
- System components comprises of the PV array and inverter.
- Grid-connected system is similar to regular electric powered system except that some or all of the electricity comes from the sun.
- The drawback of these battery less systems is that they provide no outage protection when the utility grid fails, these systems cannot operate.

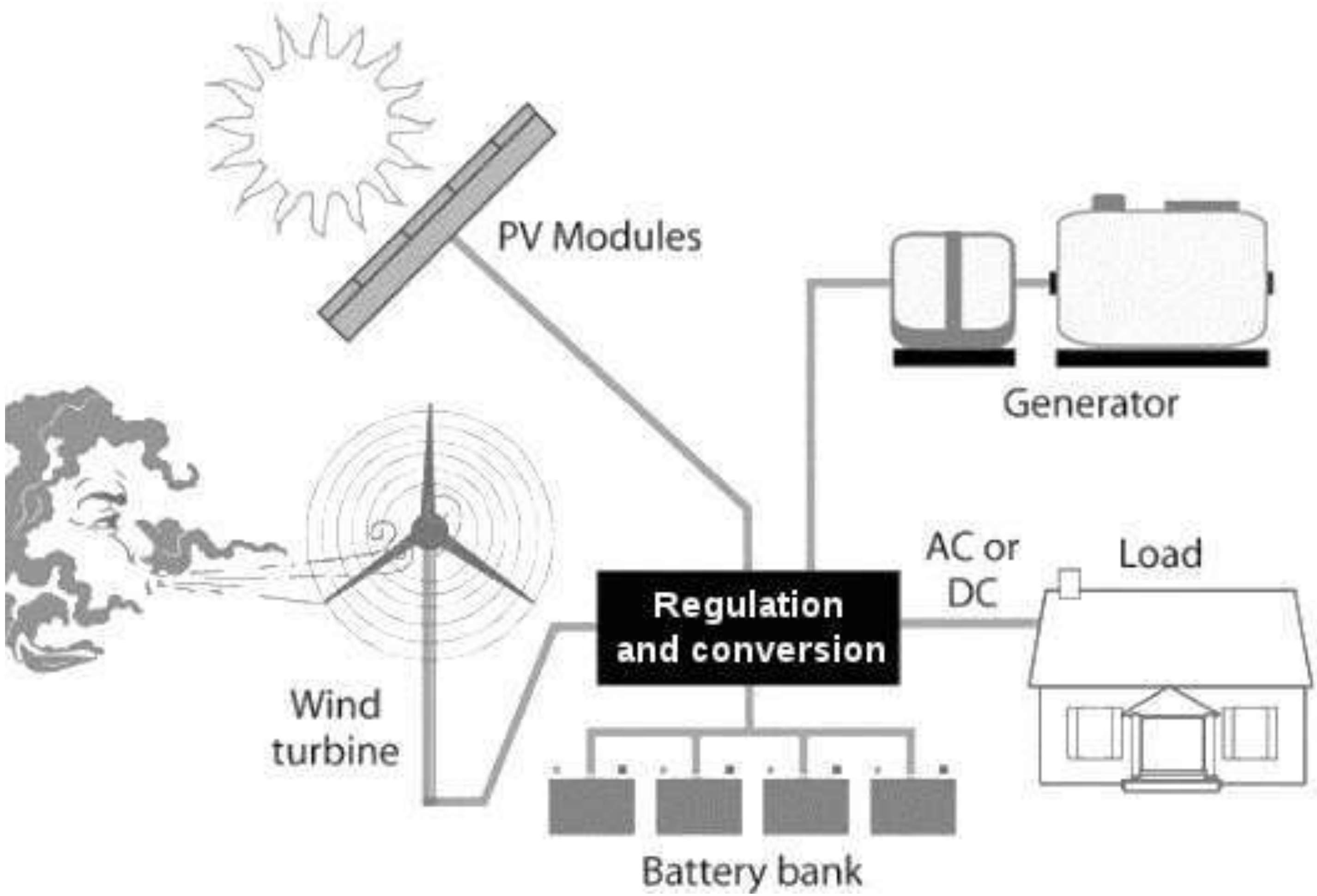
Grid tied system without battery back up



Hybrid system

- Hybrid system tries to combine multiple sources of power to maximize availability of power.
- It may source energy from sun, wind or diesel generator and back it up with battery.
- Multiple sources of generation allows for complementary sources and backup.
- For instance, when it is sunny out the PV array will charge the battery; if it is cloudy and windy, a wind turbine can charge the batteries.

Hybrid power systems



Hybrid power systems

- Array size and battery bank capacity can typically be reduced and not having to oversize for periods of no sun
- More complex system design and installation
- Multiple power sources can increase upfront expenses.
- Wind turbines and generators require regular maintenance.