Unit 2
Solar PV Systems

Topics to be covered in this unit:

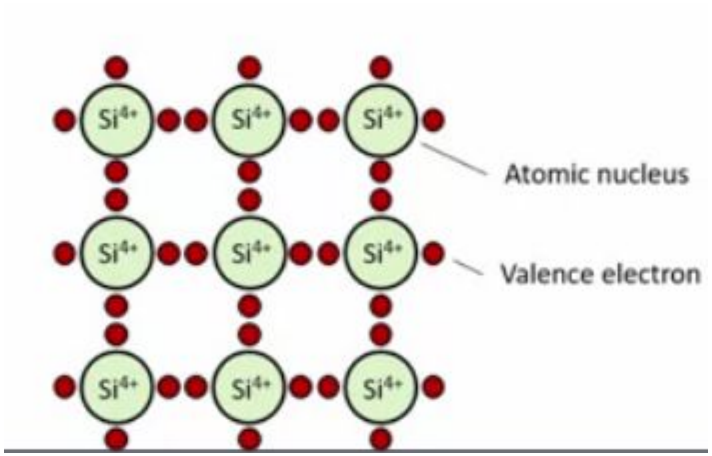
Solar PV Systems:

- Solar cell fundamentals,
- characteristics,
- classification,
- construction of module, panel and array,
- stand-alone and grid connected;
- Applications –Street lighting, domestic lighting and solar water pumping systems.

Solar cell fundamentals:

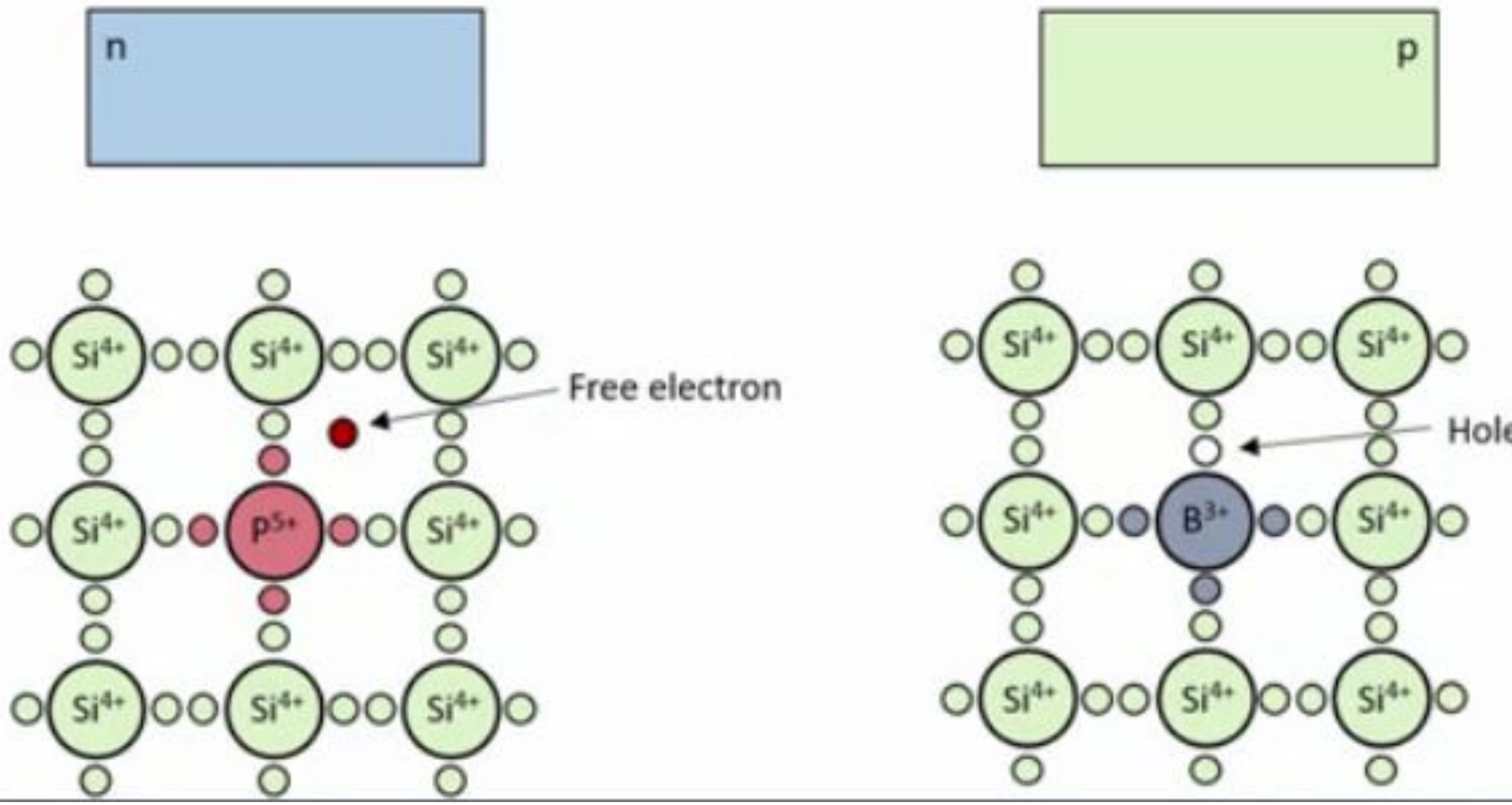
- Solar cell is a device which converts solar energy into electrical energy.

- Silicon is the most widely used material to manufacture solar cell.

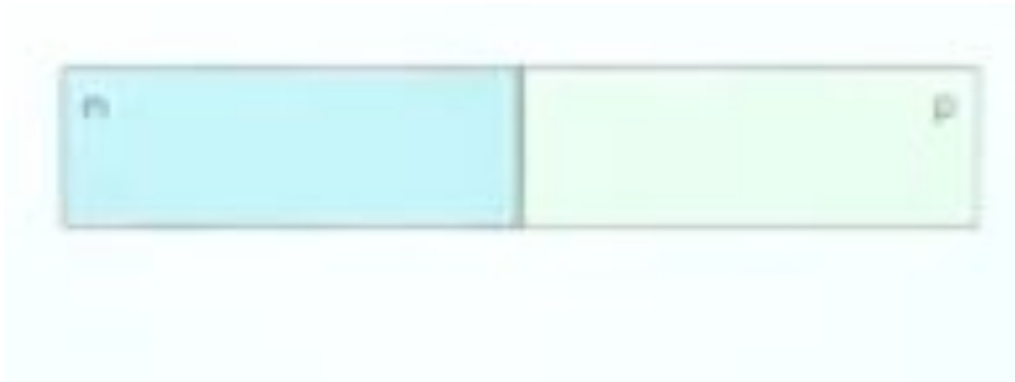


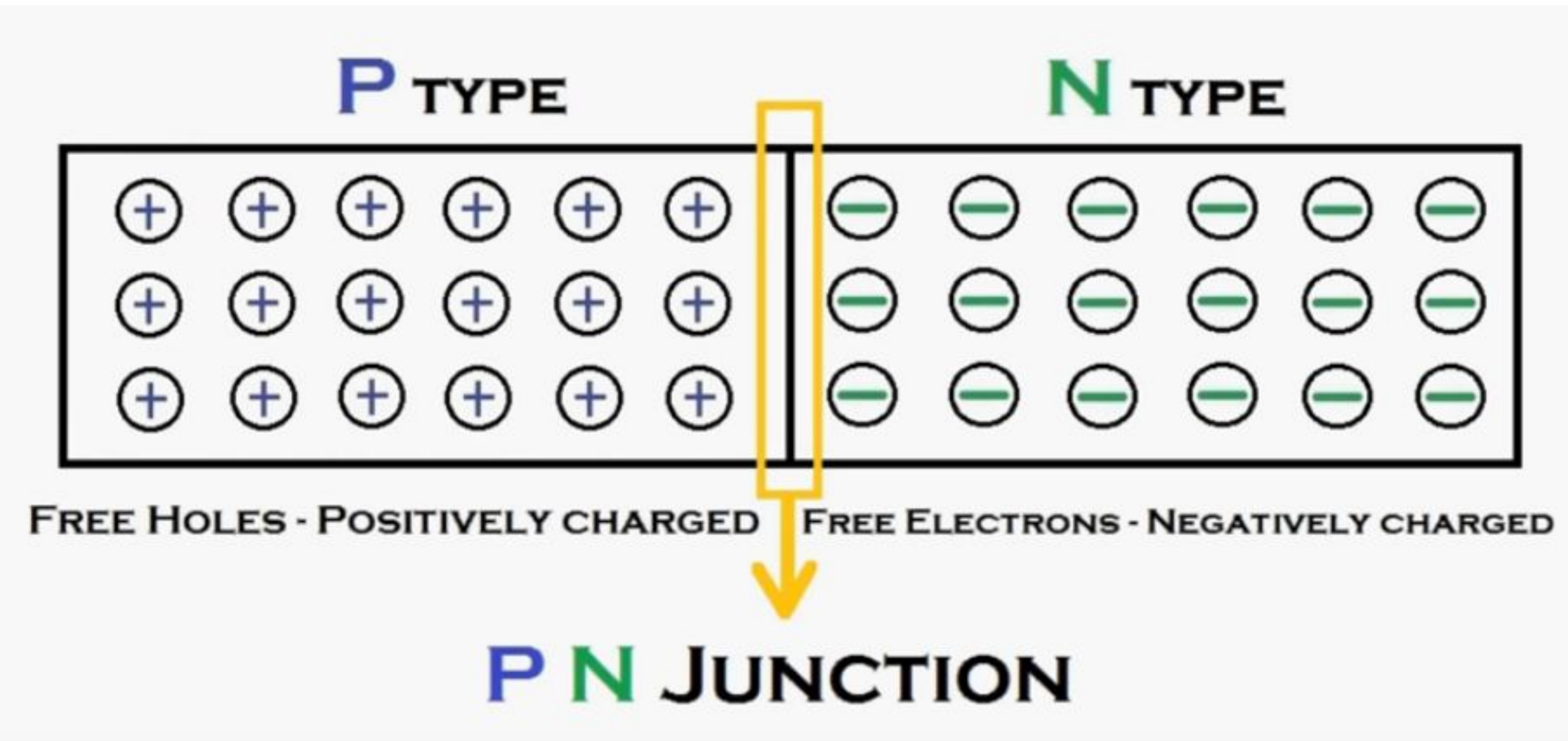
- Si has 4 valence electrons
- Silicon itself is not sufficient to create solar cell

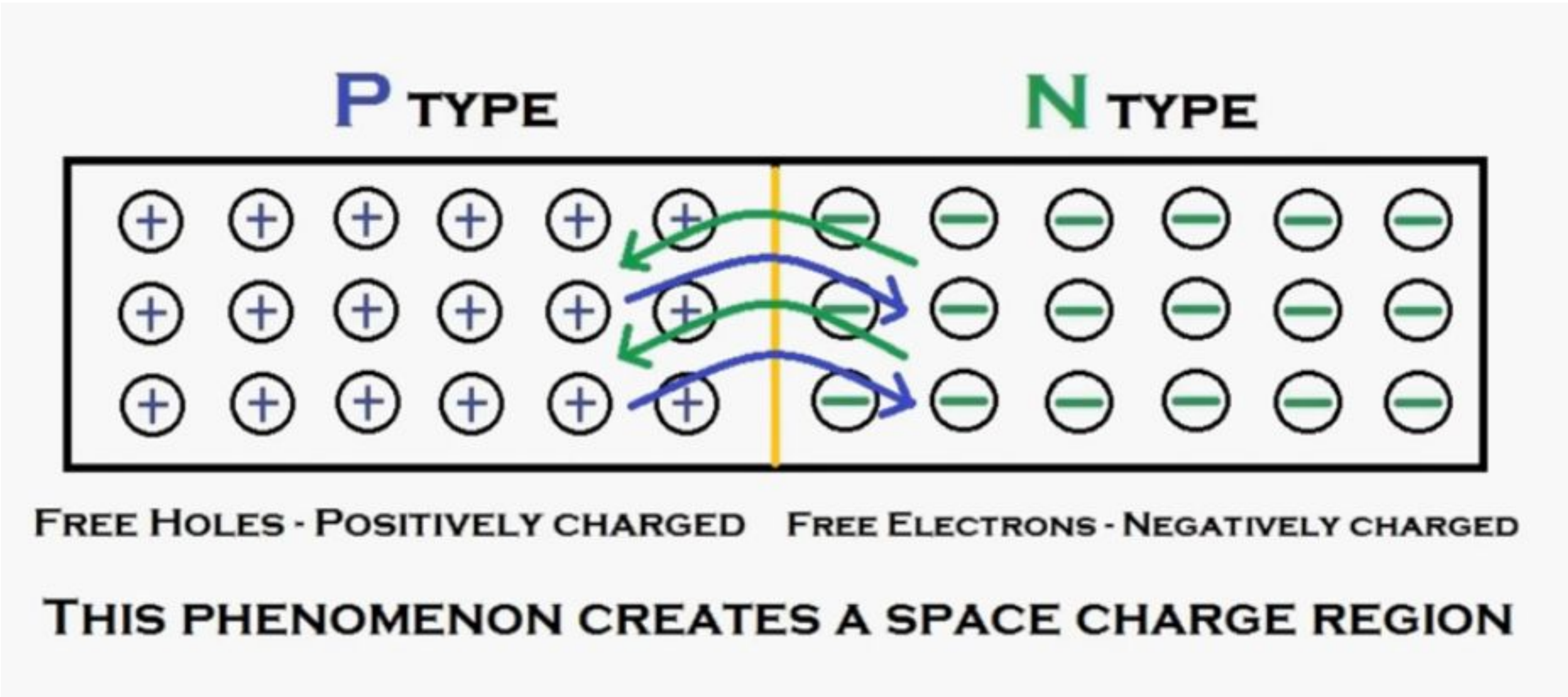
Doping

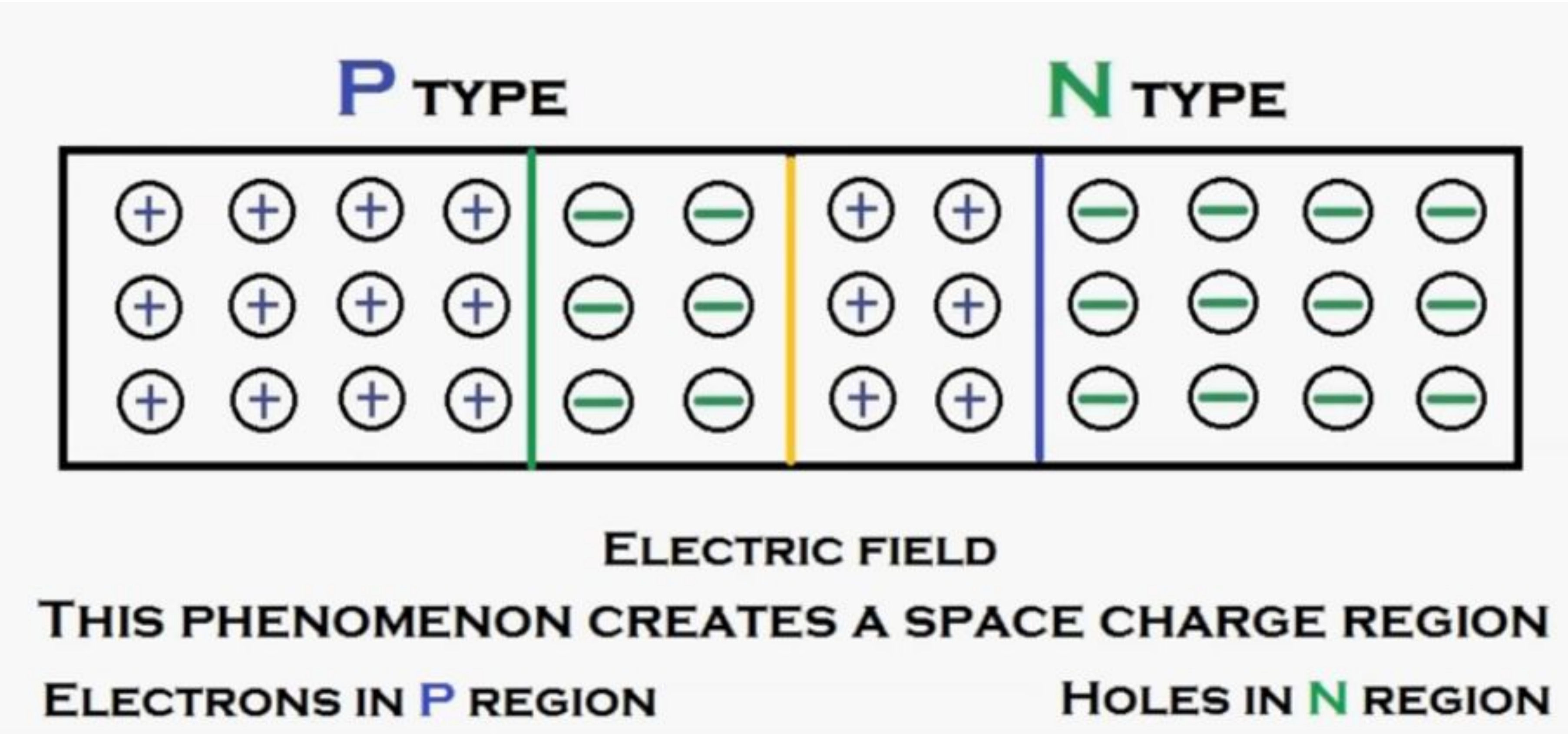


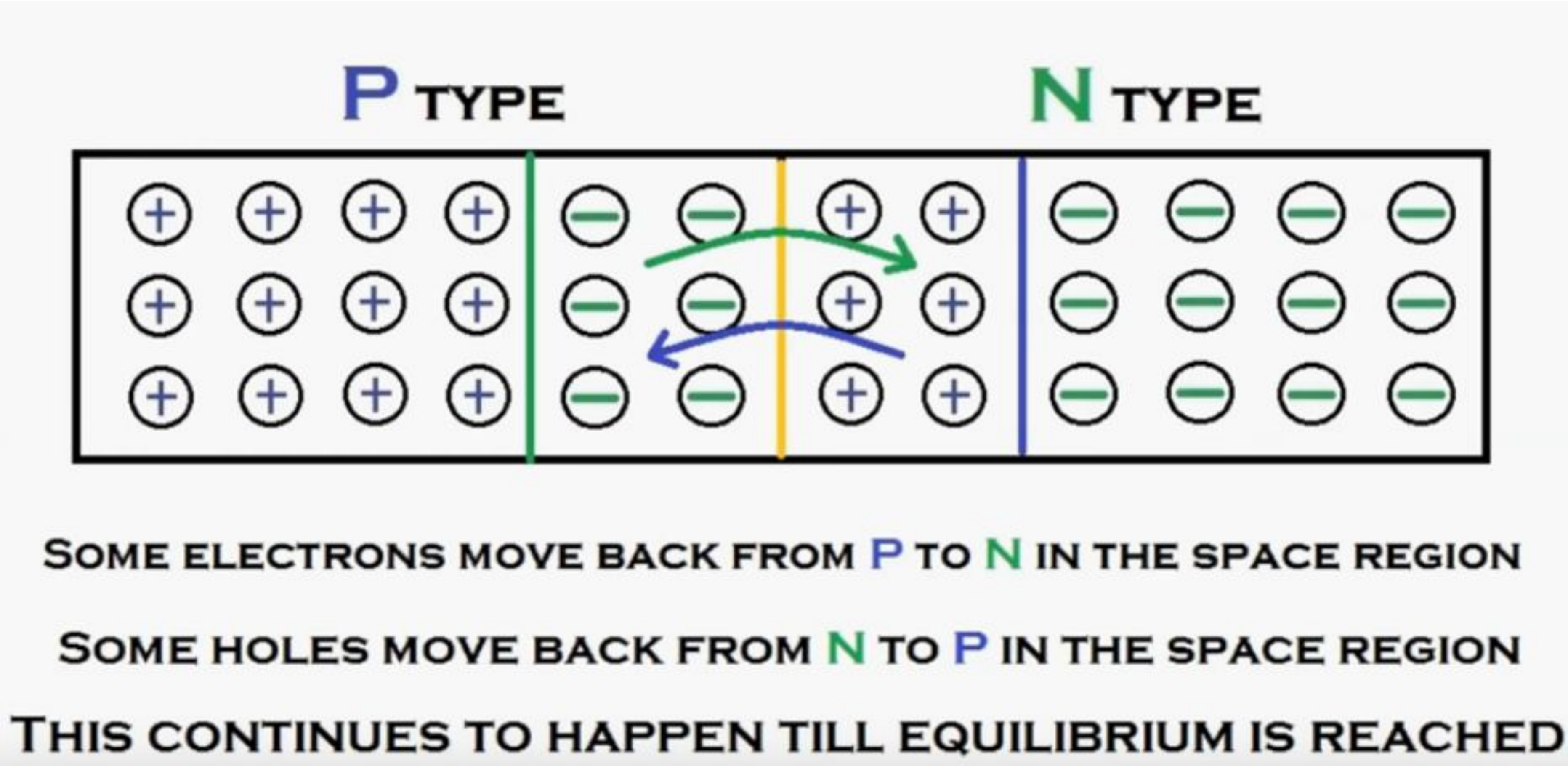
- Doping helps to create excess electrons and holes in the system.
- N-type has excess of electrons
- P-type has excess of holes


n
p


P TYPE
N TYPE
FREE HOLES - POSITIVELY CHARGED
FREE ELECTRONS - NEGATIVELY CHARGED
P N JUNCTION

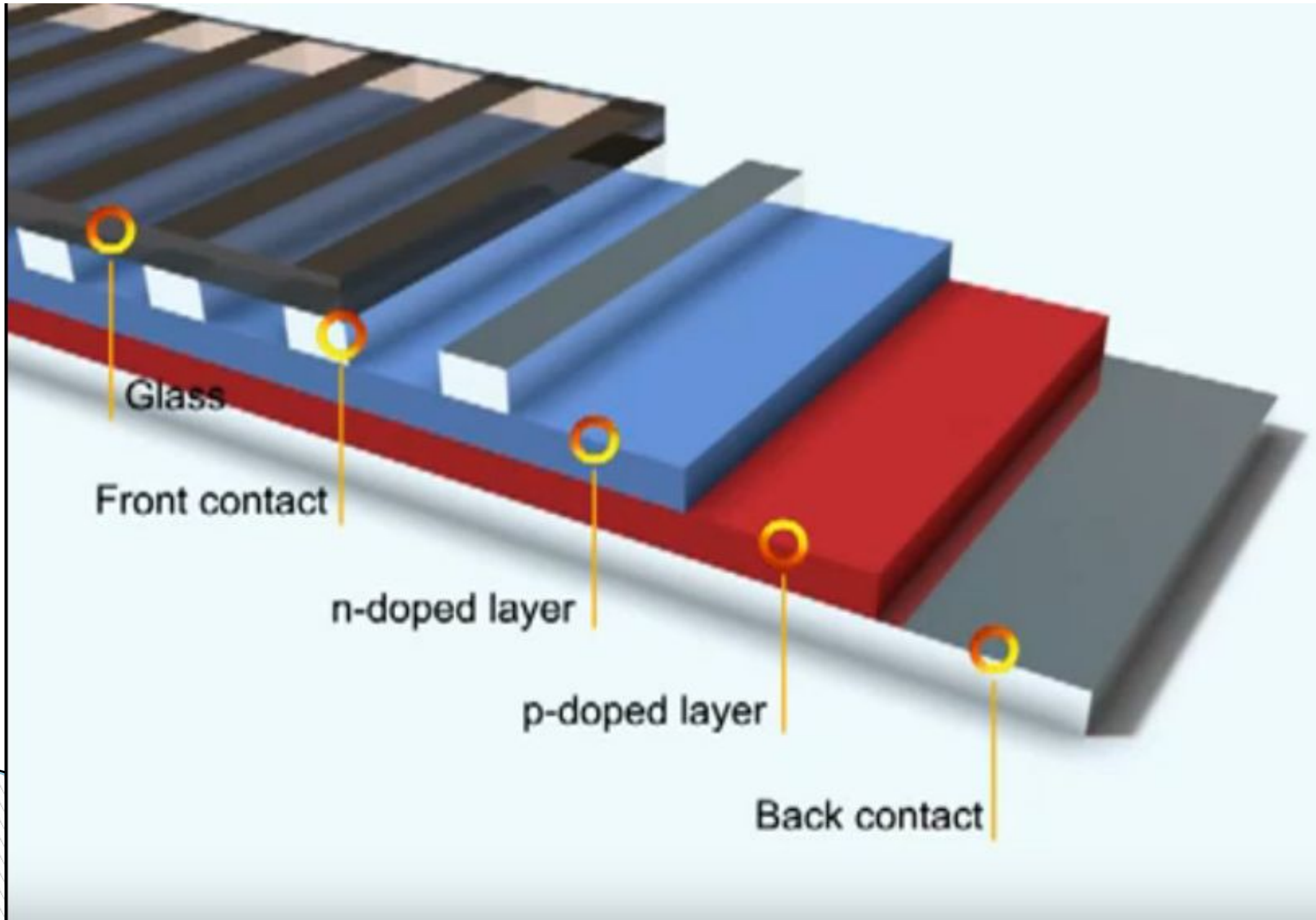

P TYPE
N TYPE
FREE HOLES - POSITIVELY CHARGED
FREE ELECTRONS - NEGATIVELY CHARGED
THIS PHENOMENON CREATES A SPACE CHARGE REGION

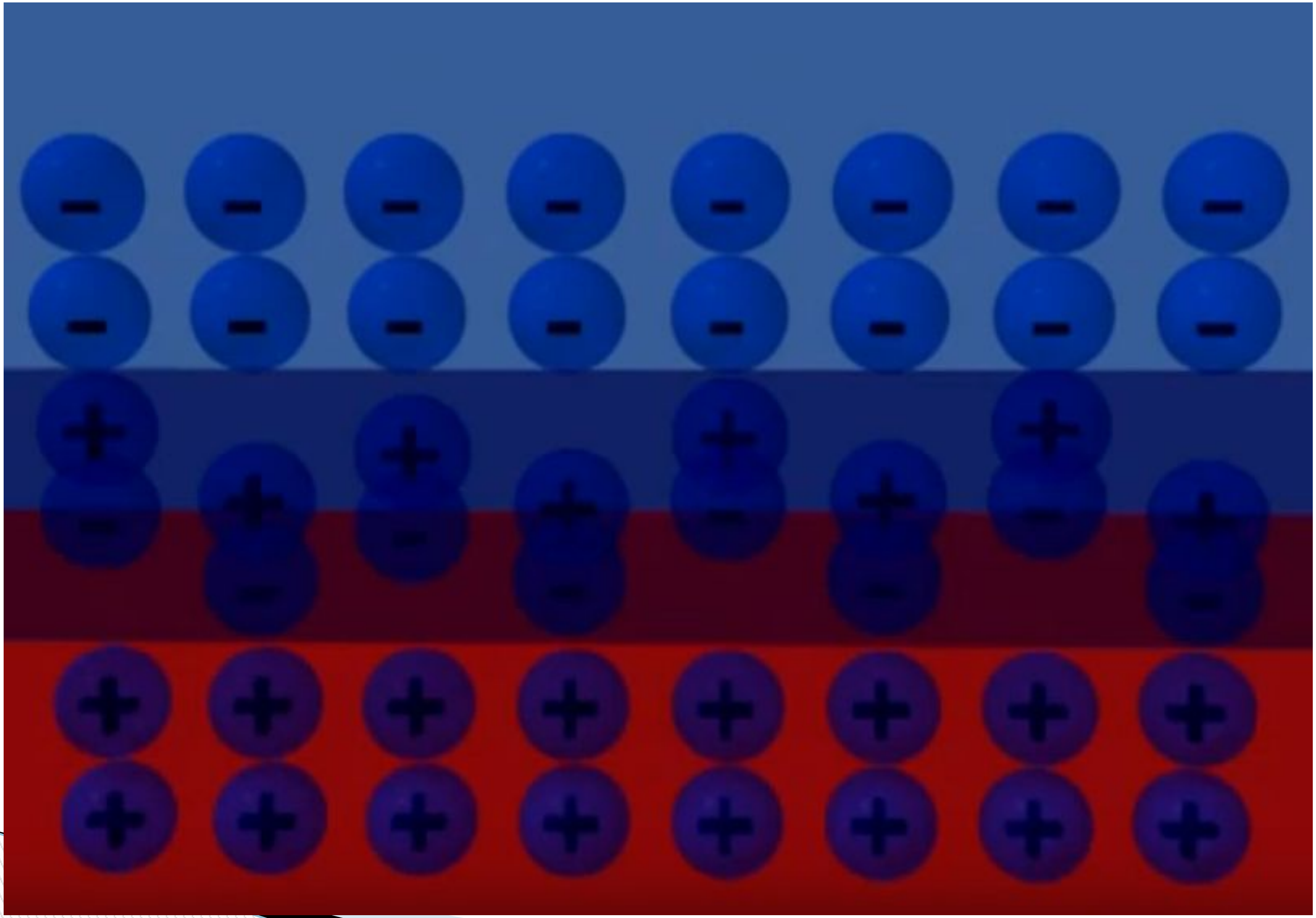

P TYPE
N TYPE
ELECTRIC FIELD
THIS PHENOMENON CREATES A SPACE CHARGE REGION
ELECTRONS IN P REGION
HOLES IN N REGION



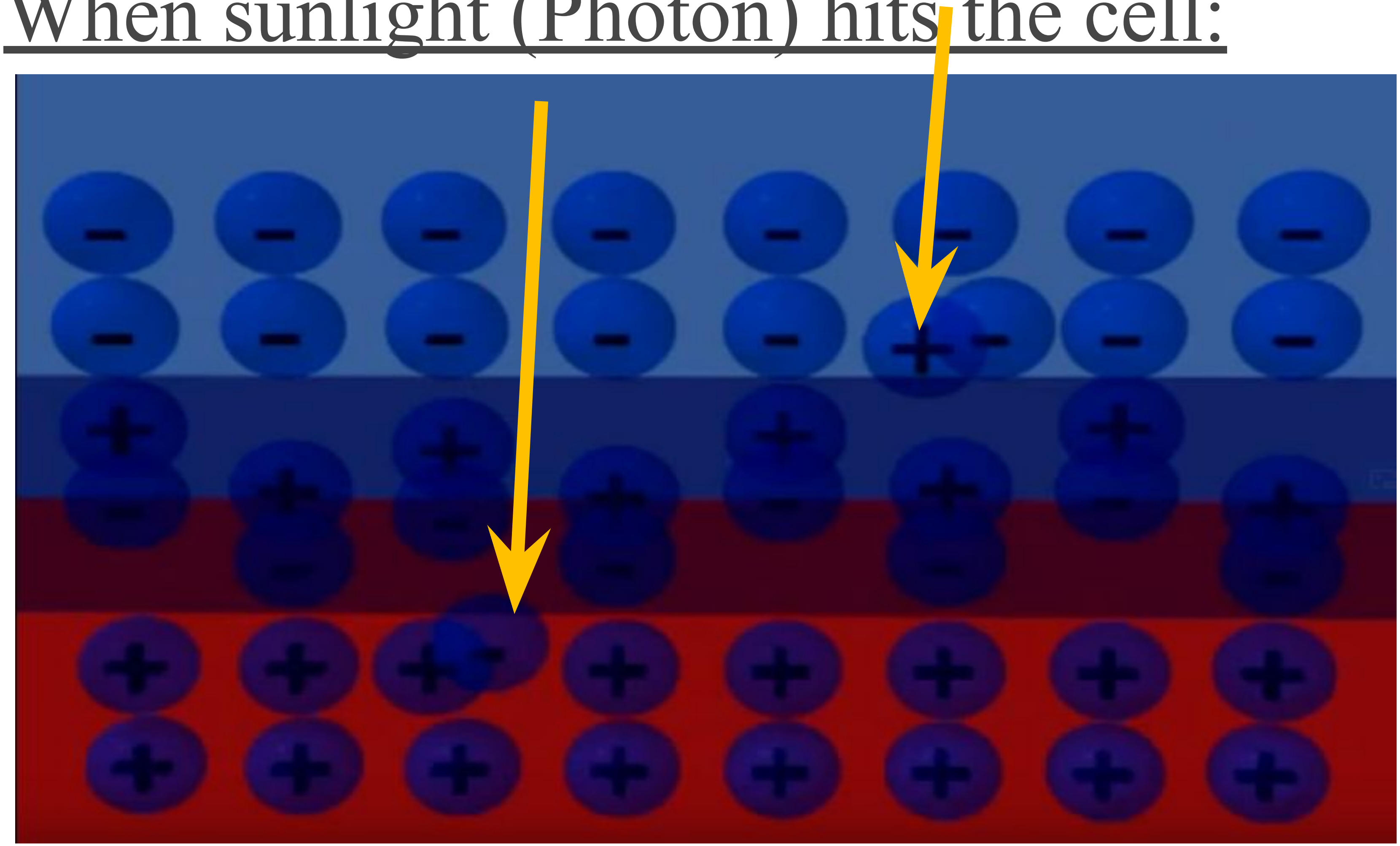
- The electric field created in the space charge region will not allow the electrons and holes to jump into the other layer.

Solar cell layers:

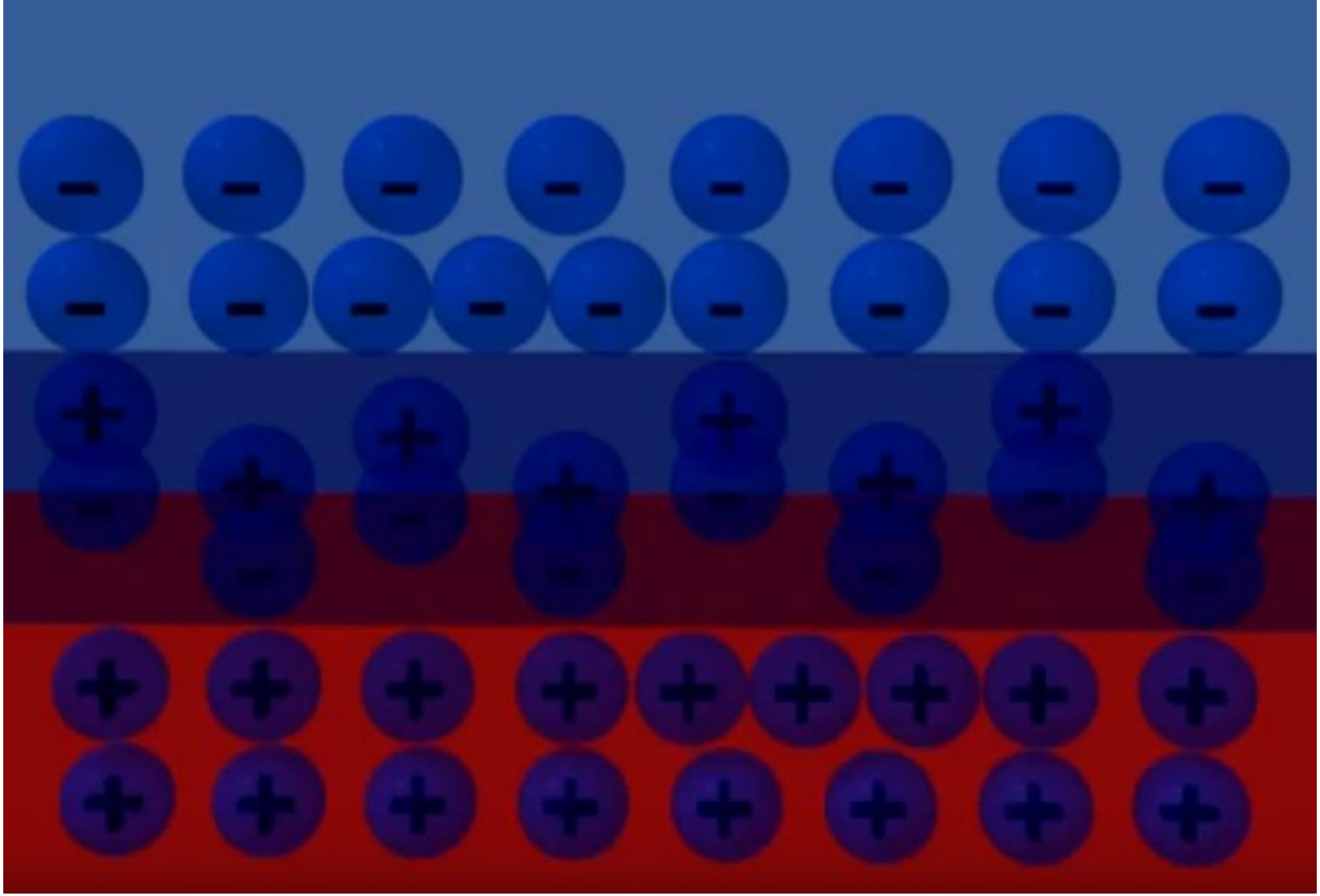




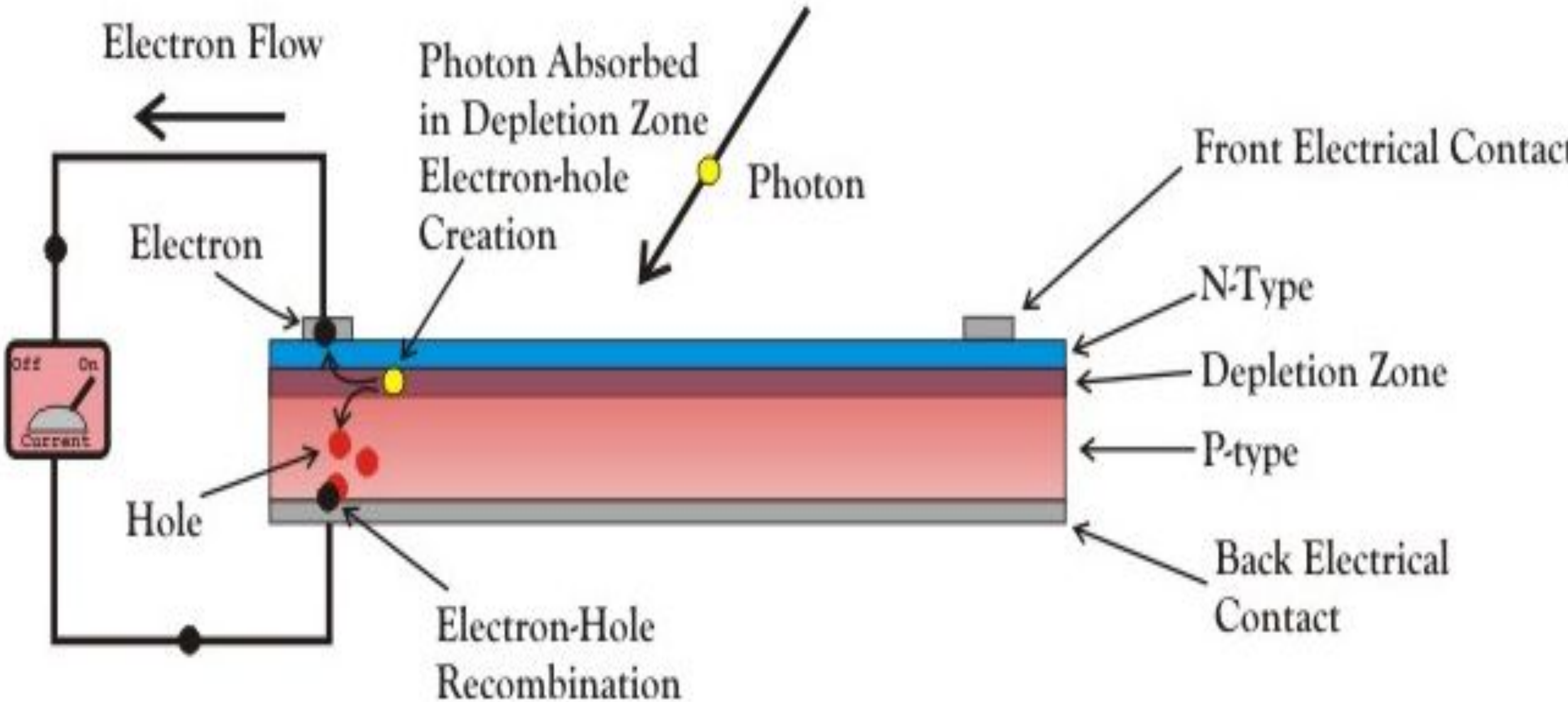
When sunlight (Photon) hits the cell:



When a photon of light is absorbed by one of these atoms it gets dislodge creating a free electron and a hole. The free electron and hole has sufficient energy to jump out of the depletion zone.



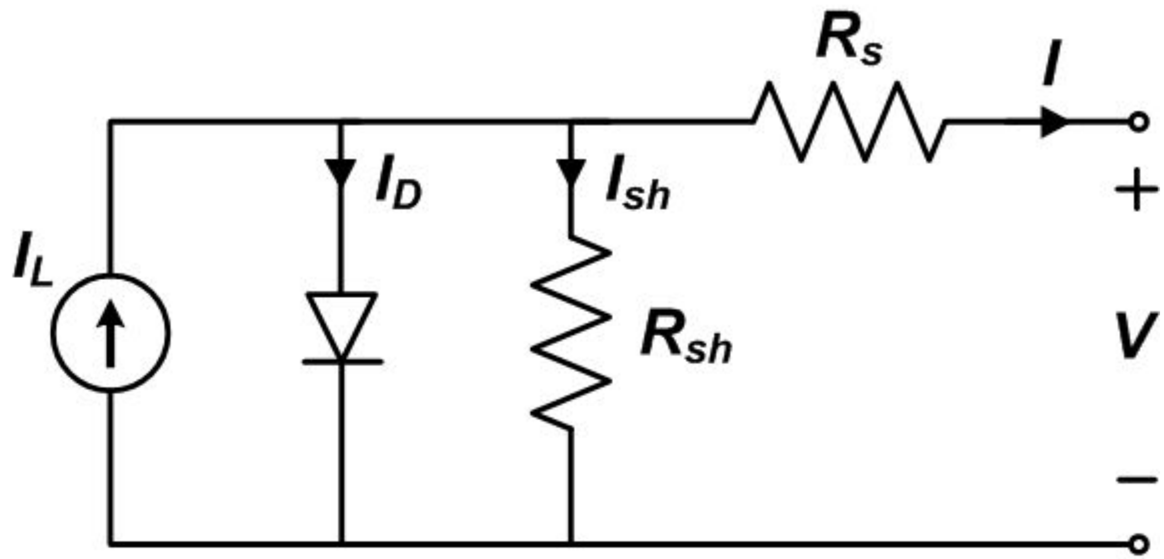
This creates an imbalance resulting in excess of electrons in N region and corresponding Holes in P region. These electrons will try to recombine with the holes in the P region.



- If there is an external circuit, then these excess electrons will that that path as shown in the above diagram
- This flow of electrons results into a DC current which can be used further.

❑Characteristics of Solar Cell:

- Electric Equivalent of solar cell:



An ideal solar cell may be modeled by a current source in parallel with a diode; in practice no solar cell is ideal, so a shunt resistance and a series resistance component are added to the model.

From the circuit, the current produced by the solar cell is given by,

$$I = I_L - I_D - I_{SH}$$

where

- I = output current (ampere)
- I_L = photogenerated current (ampere)
- I_D = diode current (ampere)
- I_{SH} = shunt current (ampere).

By the Shockley diode equation, the current diverted through the diode is:

$$I_D = I_0 \left\{ \exp\left[\frac{V_j}{nV_T} \right] - 1 \right\}$$ [7]

where

- I_0 = reverse saturation current (ampere)
- n = diode ideality factor (1 for an ideal diode)
- q = elementary charge
- k = Boltzmann's constant
- T = absolute temperature
- $V_T = kT/q$, the thermal voltage. At 25 °C, $V_T \approx 0.0259$ volt.

By Ohm's law, the current diverted through the shunt resistor is:

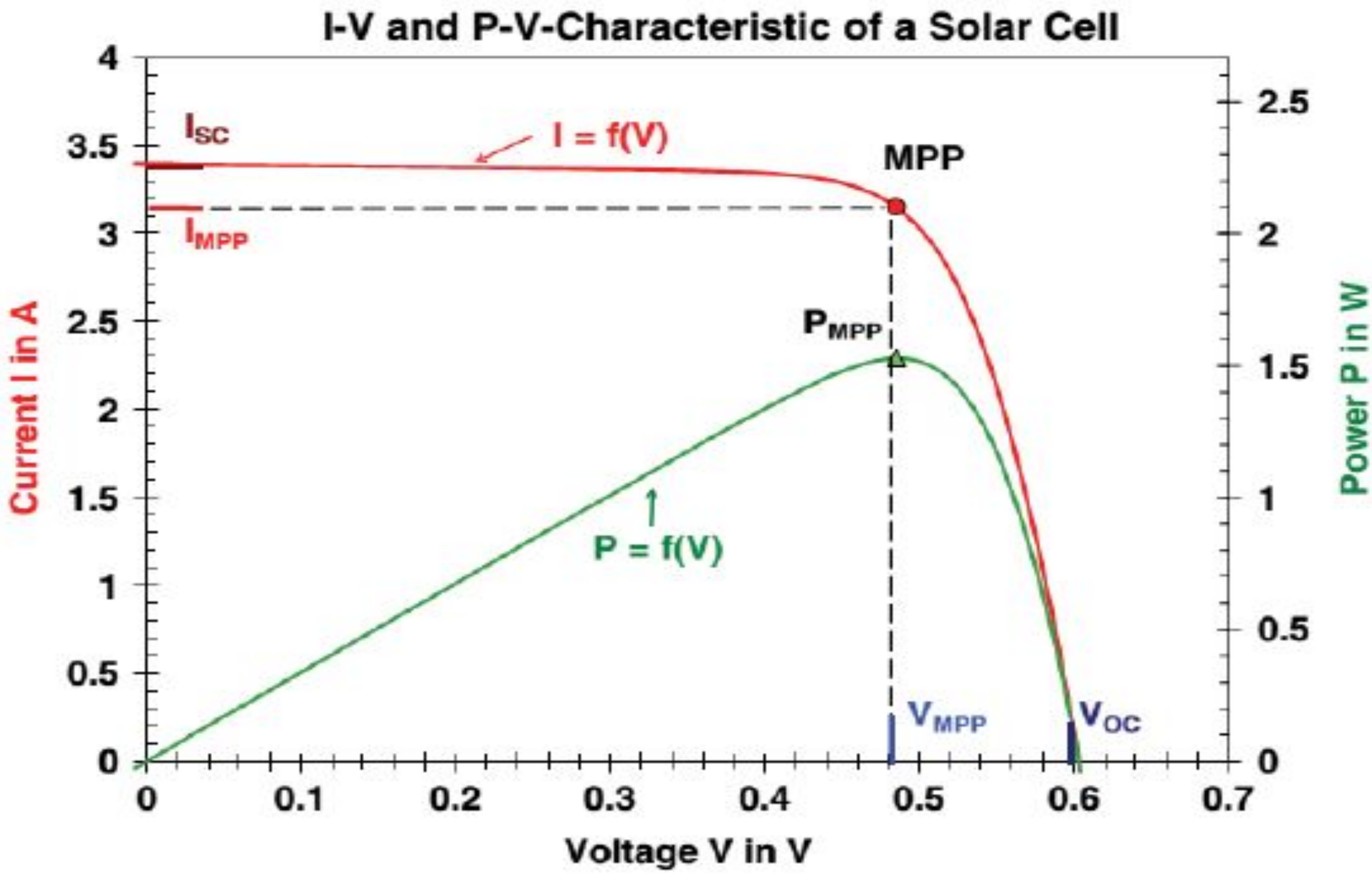
$$I_{SH} = \frac{V_j}{R_{SH}}$$

where

- R_{SH} = shunt resistance (Ω).

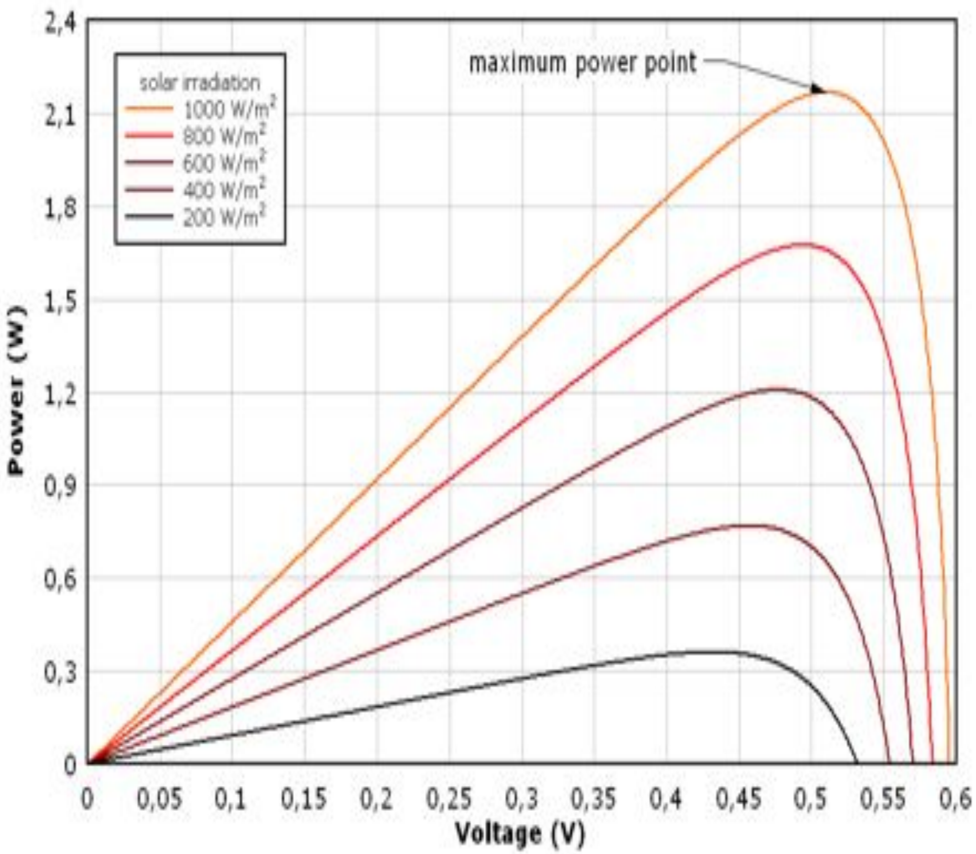
Substituting these into the first equation produces the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage:

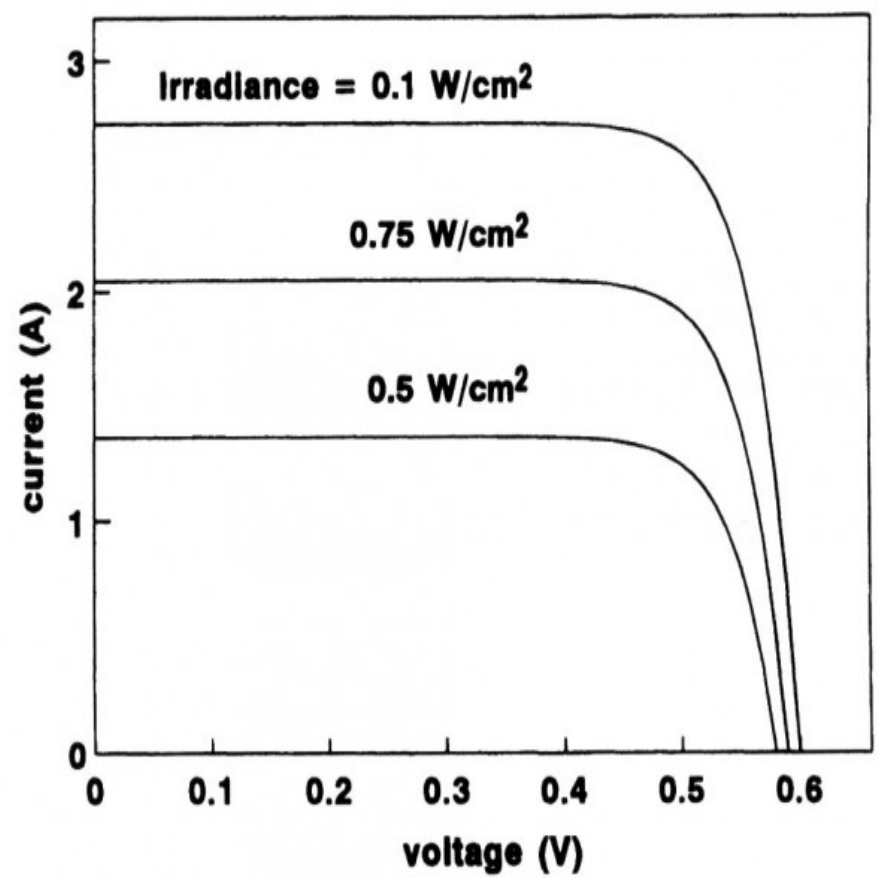
$$I = I_L - I_0 \left\{ \exp\left[\frac{V + IR_S}{nV_T} \right] - 1 \right\} - \frac{V + IR_S}{R_{SH}}.$$



- **At short circuit condition (Fault, i.e. + & - terminal coming in contact), I is maximum and V is Zero**
- **At Open circuit condition (When No load is connected across the + & - terminals), V is maximum and I is Zero**

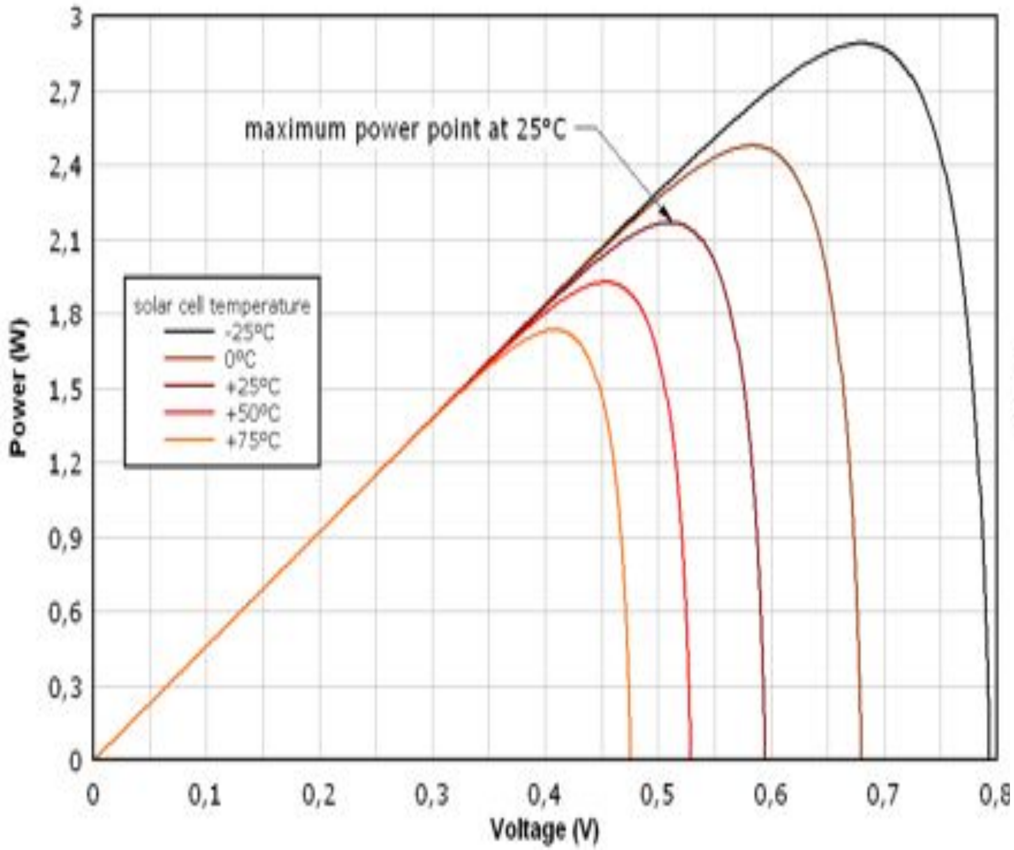
Variation of output power w.r.t change in irradiation:

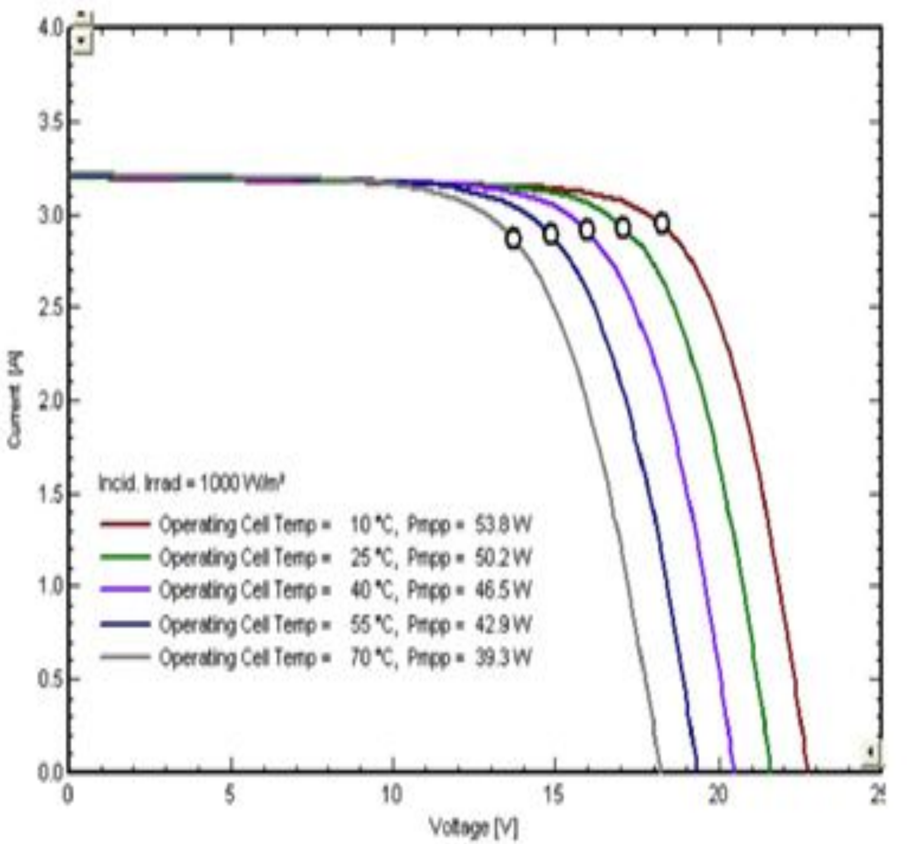




Change in the Irradiation majorly affects the output current of the panel.

Variation of output power w.r.t change in Temperature:





Change in the temperature majorly affects the output voltage of the panel.

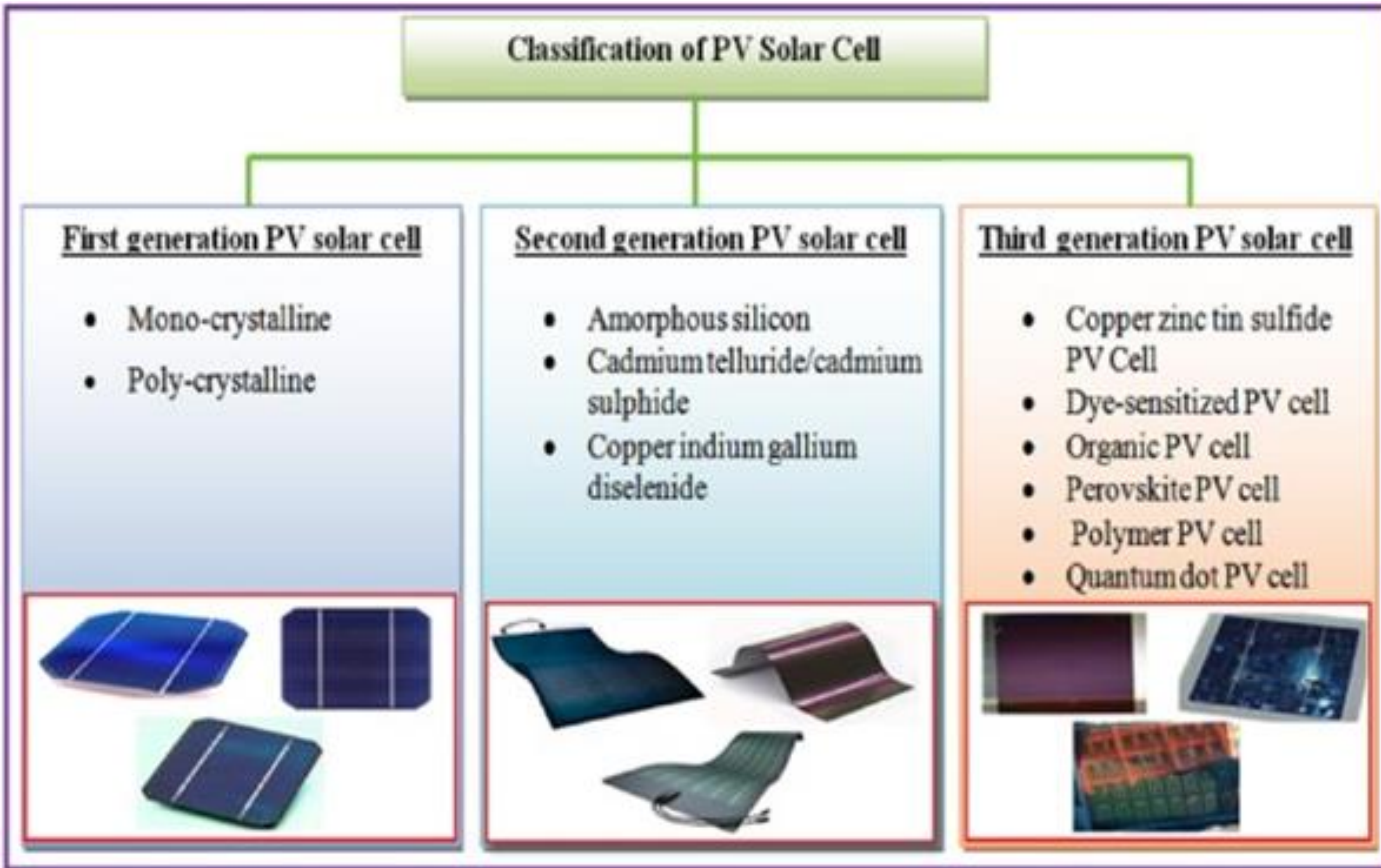
- Maximum output is obtained at STC (standard test condition), i.e.

Temperature = 25 degrees celsius and

Irradiation = 1000 W/m2

(100 W solar panel can generate, 100 W only at STC)

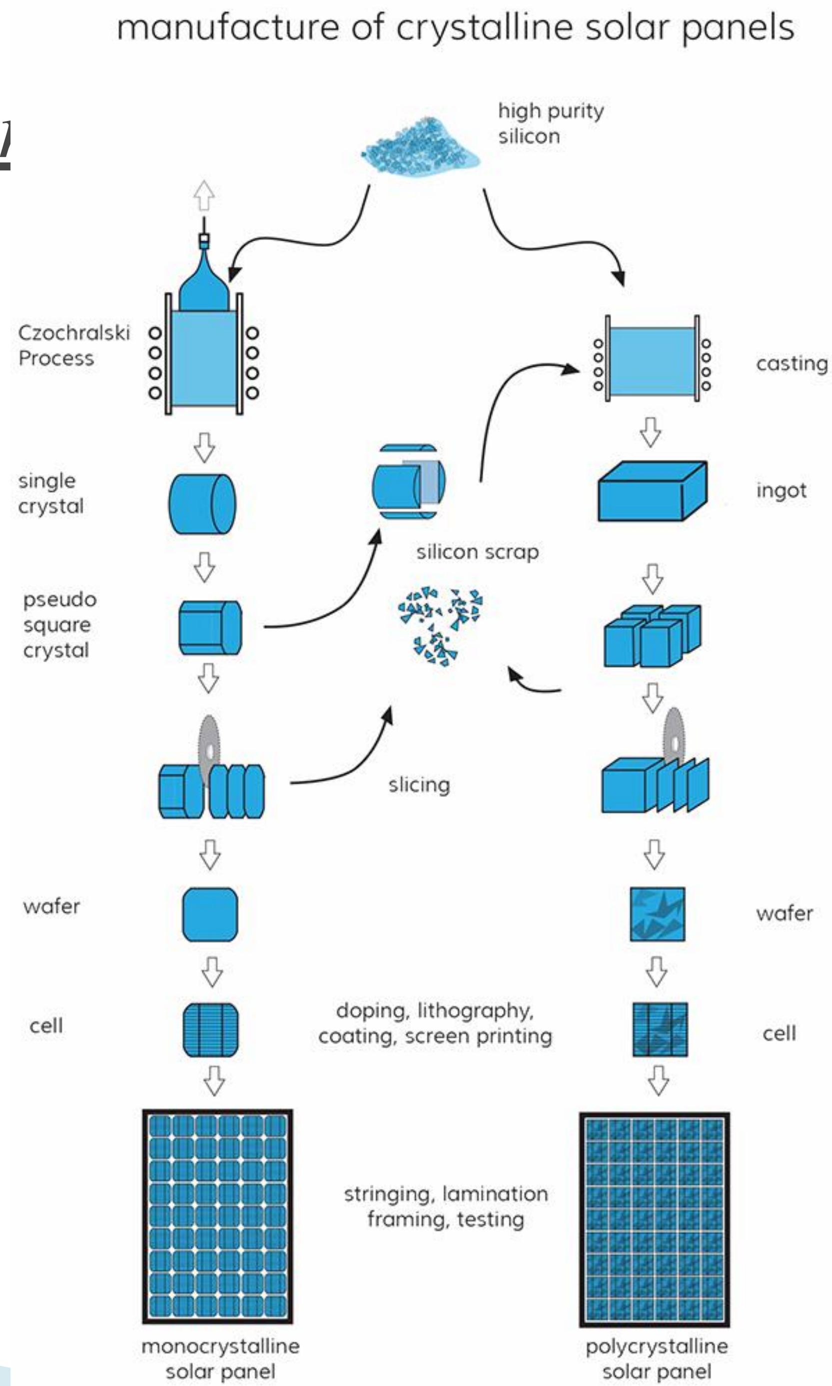
❑Classification of Solar Cells:



First Generation Solar Pa

1. **Monocrystalline Solar Panels**

2. **Polycrystalline Solar Panels**

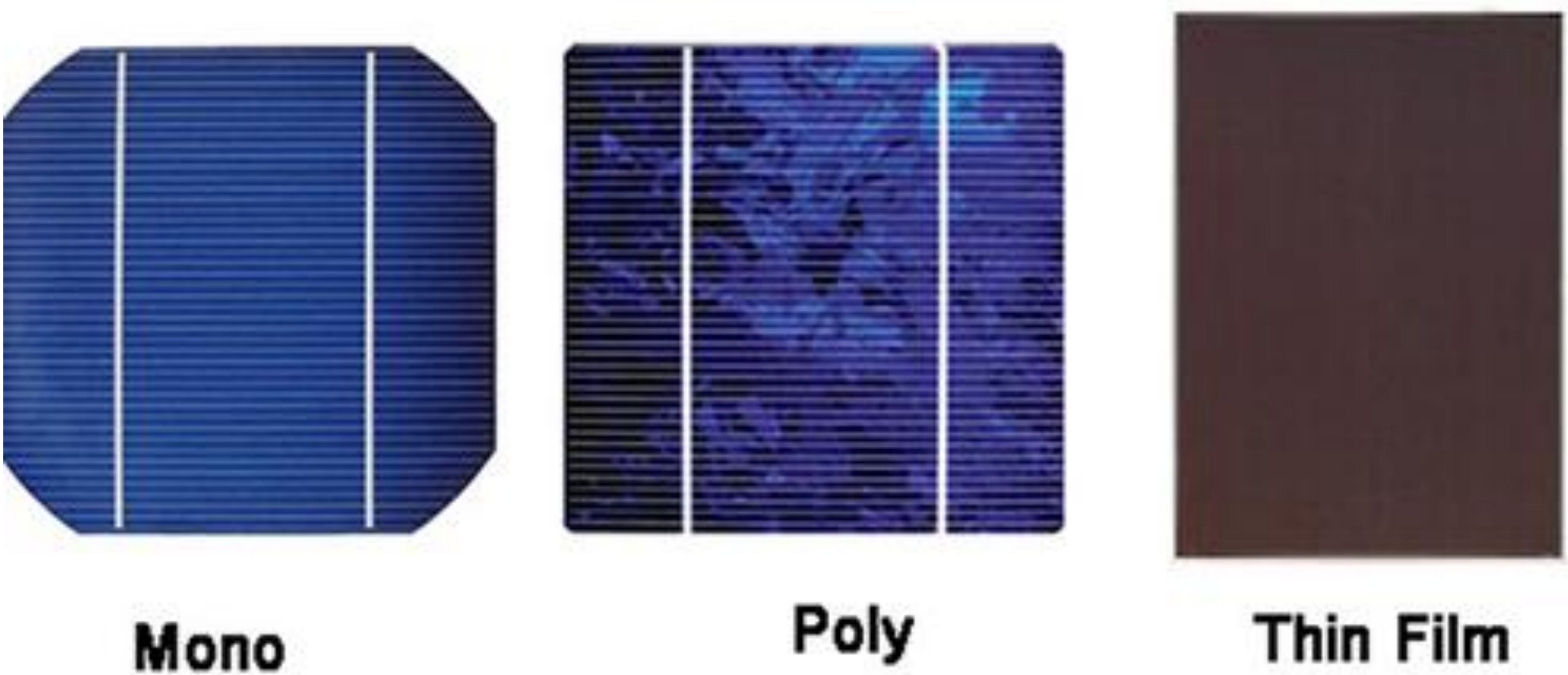


1. Monocrystalline Solar Panels

- The first commercially available solar cells were made from monocrystalline silicon.
- Made from extremely pure form of silicon.
- To produce these, a seed crystal is pulled out of a mass of molten silicon by the process called czochralski process, creating a cylindrical ingot with a single, continuous, crystal lattice structure.
- The Mono panels are manufactured using a single continuous crystal structure having very few impurities in the cell thus making them very efficient. (20% efficiency)
- They use much less roof space to generate an amount of power equivalent to polycrystalline solar cells.

2. Polycrystalline Solar cells

- In the manufacturing process of polycrystalline cells, molten silicon in a rectangular vat is allowed to cool down.
- This cooling down process gives the panel its squared edges but instead of a single silicon crystal in the vat there are multiple crystal grains within the polycrystalline solar cells.
- Efficiency of these cells is around 11 to 16%


Mono
Poly
Thin Film

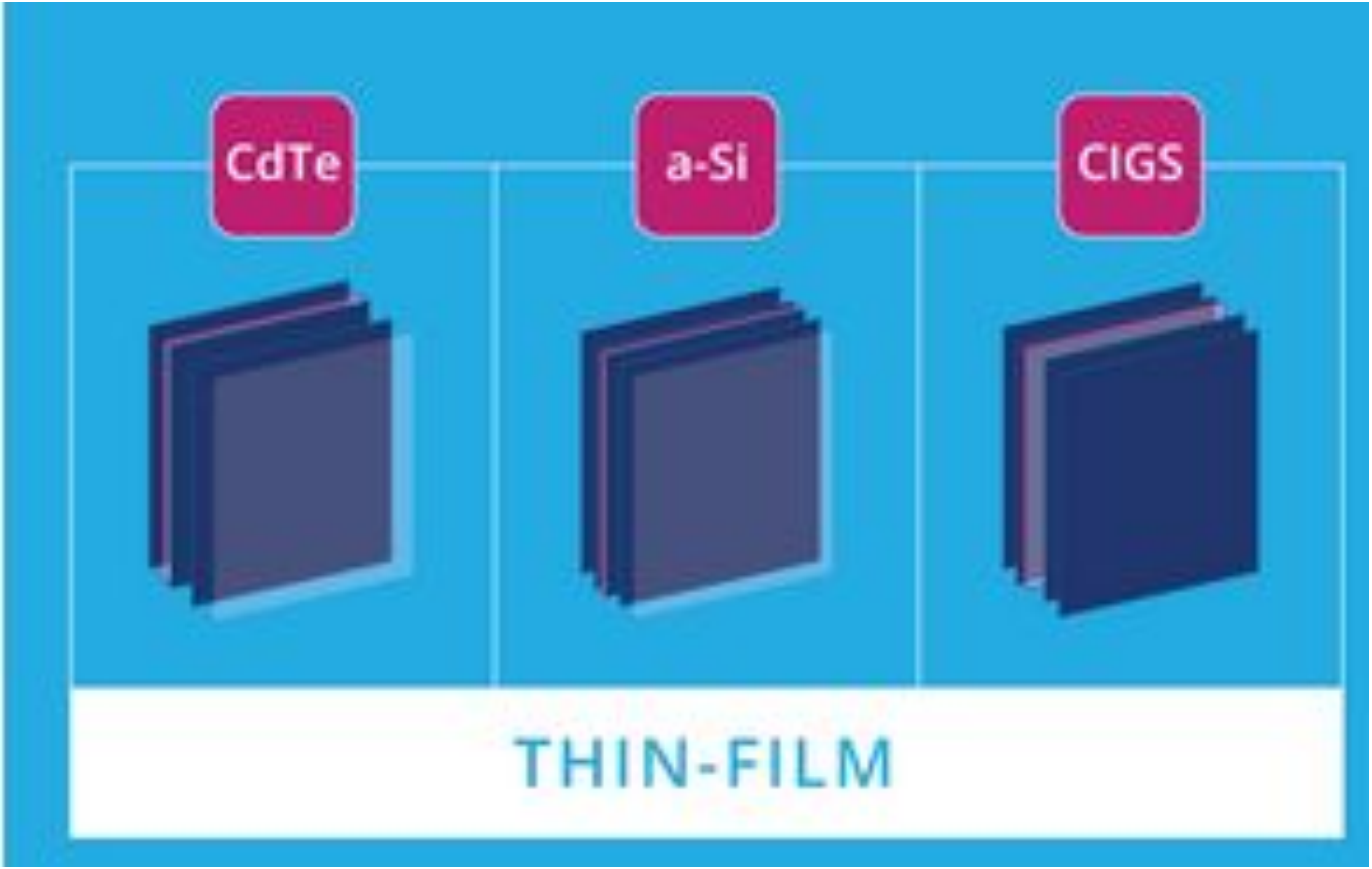
Second Generation solar cell:

- The manufacturing process of these types of solar panels is relatively easier and involves depositing one or multiple films of photovoltaic Amorphous Silicon materials onto the back support sheet known as substrate
- low in cost and lightweight.
- These cells are flexible which makes it possible to use these cells in multiple applications
- These panels have an efficiency rate as low as 7-9 percent only.
- Thin film solar cells are less affected by high temperatures.
- Require a lot of space

- Unlike monocrystalline and polycrystalline solar panels, thin-film panels are made from a variety of materials. The most prevalent type of thin-film solar panel is made from **cadmium telluride** (CdTe). To make this type of thin-film panel, manufacturers *place a layer of CdTe between transparent conducting layers that help capture sunlight.* This type of thin-film technology also has a glass layer on the top for protection.

- Thin-film solar panels can also be made from **amorphous silicon** (a-Si), which is similar to the composition of monocrystalline and polycrystalline panels. Though these thin-film panels use silicon in their composition, they are not made up of solid silicon wafers. Rather, they're composed of non-crystalline silicon *placed on top of glass, plastic, or metal.*

- Lastly, **Copper Indium Gallium Selenide** (CIGS) panels are another popular type of thin-film technology. CIGS panels have all **four elements placed between two conductive layers** (i.e. glass, plastic, aluminum, or steel), and electrodes are placed on the front and the back of the material to capture electrical currents.


CdTe
a-Si
CIGS
THIN-FLIM

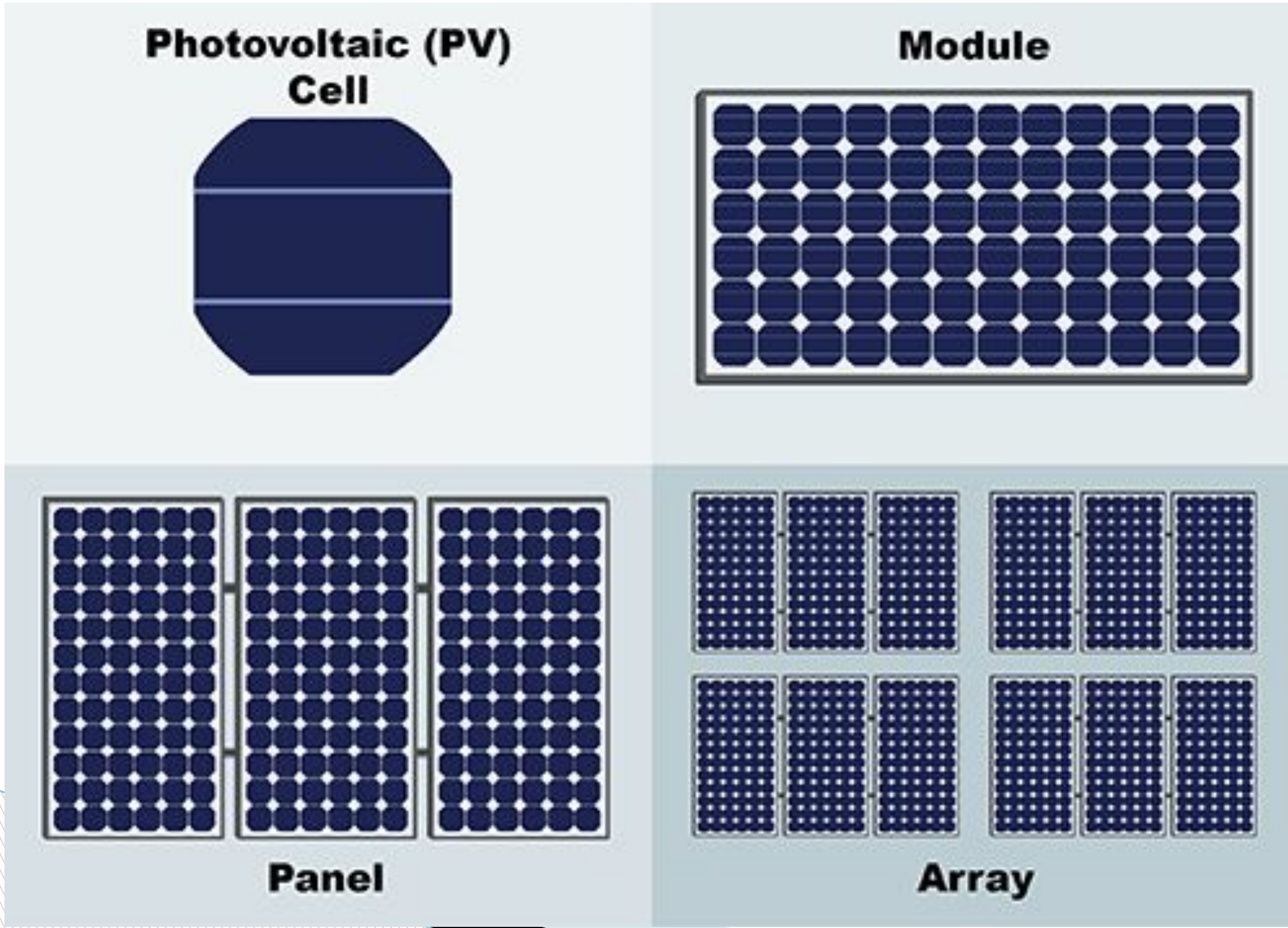
Third Generation Solar Panels

- The third generation types of solar panels employ thin film technologies that are currently undergoing research and development to make them perfect for the growing solar market.

- Some of these new age solar panels make use of organic materials while some use inorganic substances like organic photovoltaics (OPVs), copper zinc tin sulphide (CZTS), perovskite solar cells, dye-sensitized solar cells (DSSCs), and quantum dot solar cells

- They have efficiency of around 30%

❑Construction of module, panel and array



Solar PV Module:

- Single solar cell output is very low.
- Needs a series parallel combination to extract a workable amount of voltage power.

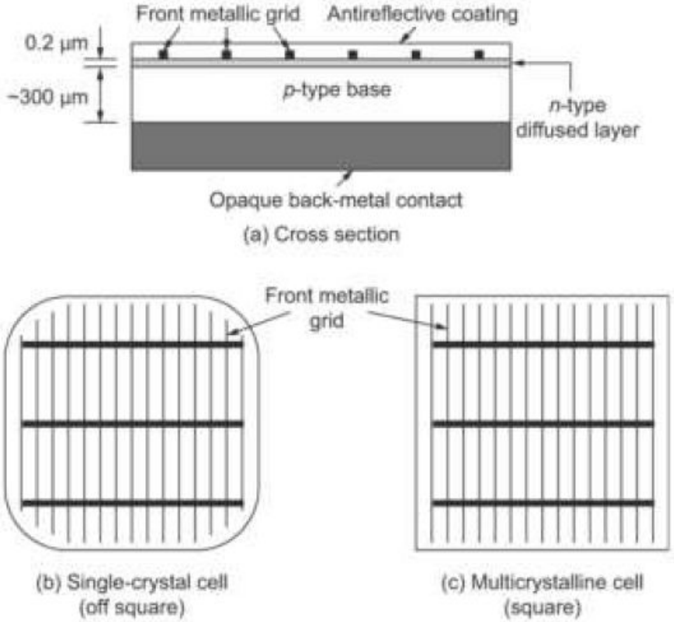
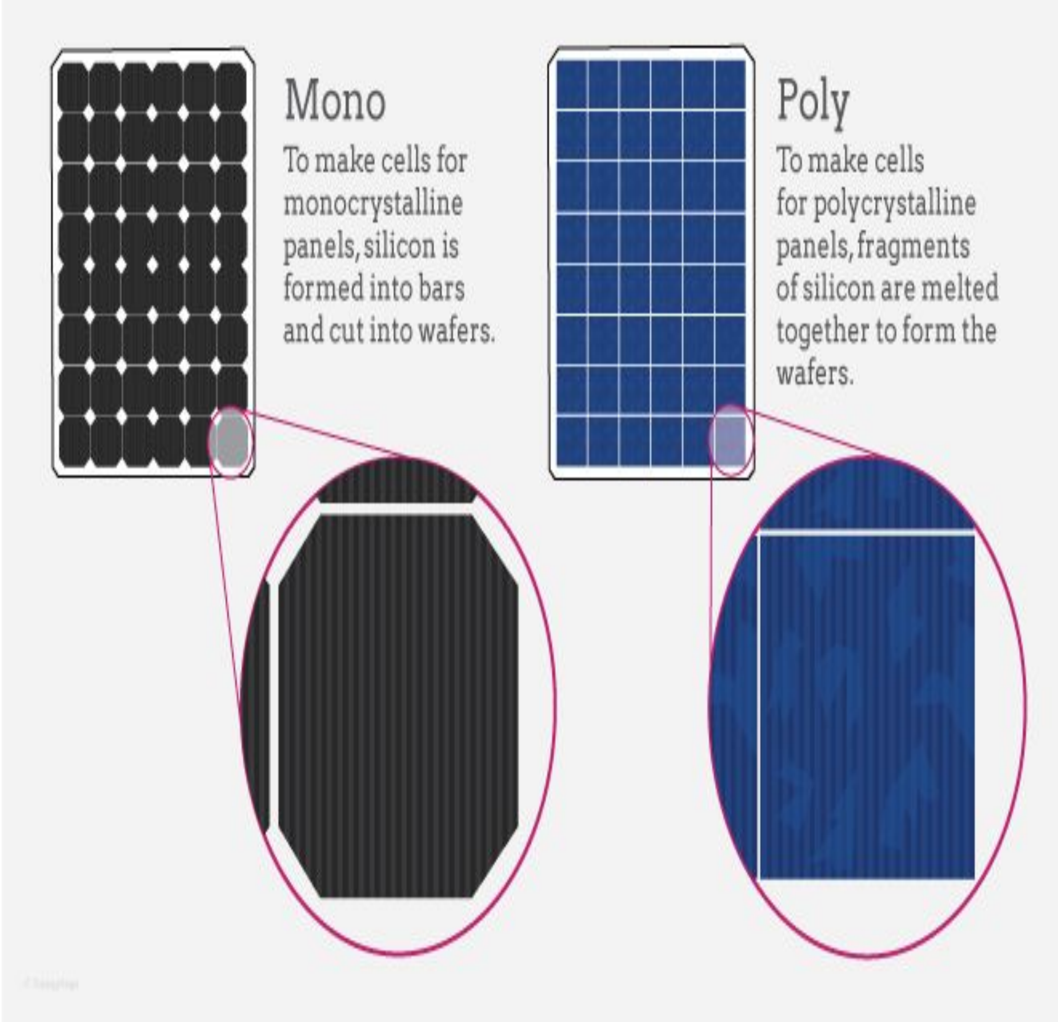


Fig. 6.16 *Construction of bulk silicon cell*



Interconnection of multiple cells to extract workable amount of power which are mounted a durable back cover of several sq. ft with a transparent glass cover on the top and which is sealed in a proper way to make it usable in the outdoor conditions.

Problems to be taken care off:

- ***Cell mismatch in the module:***
  - All the cells used must have same specification, i.e. Voc, Isc, Vmpp, Impp. Else there will be power loss which will occur .

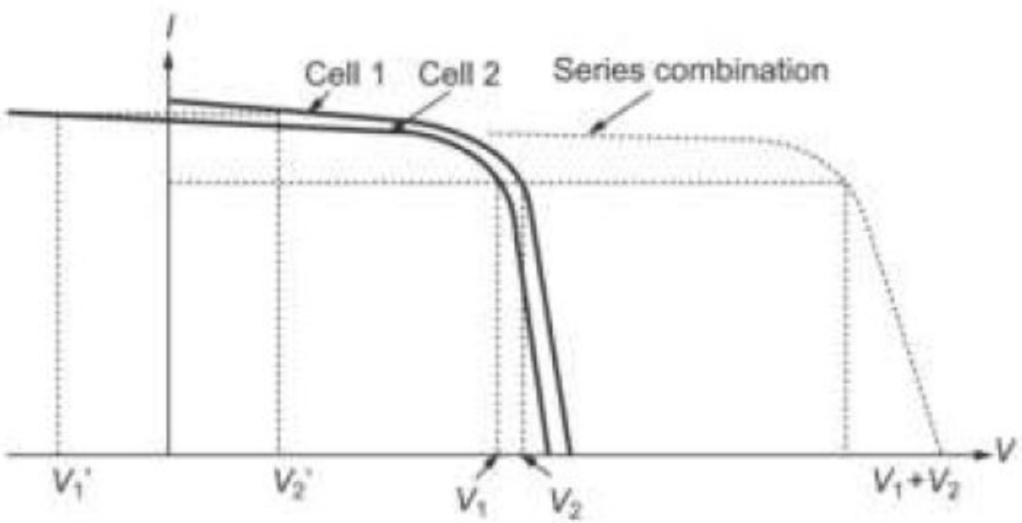


Fig. 6.17 *Composite characteristic of two cells in series*

To reduce mismatch losses, modules are fabricated from cells belonging to same batch. Also, *cell sorting* is carried out to categorize cells having matched parameters with specified tolerance.

Effect of Shadow:

Shadowing on the perticular cells will stop the generation in those cells keeping the other cells active, if the active cells are more then the excessive current generated will damage the shadowed cell and this effect is called hot spot.

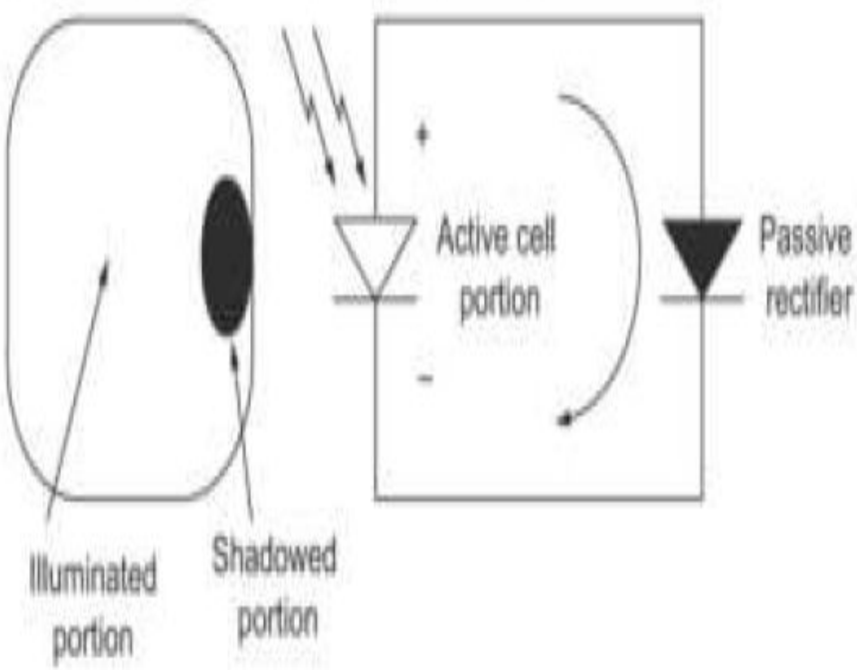


Fig. 6.18 Partial shadowing of a cell

Solution for hot spot

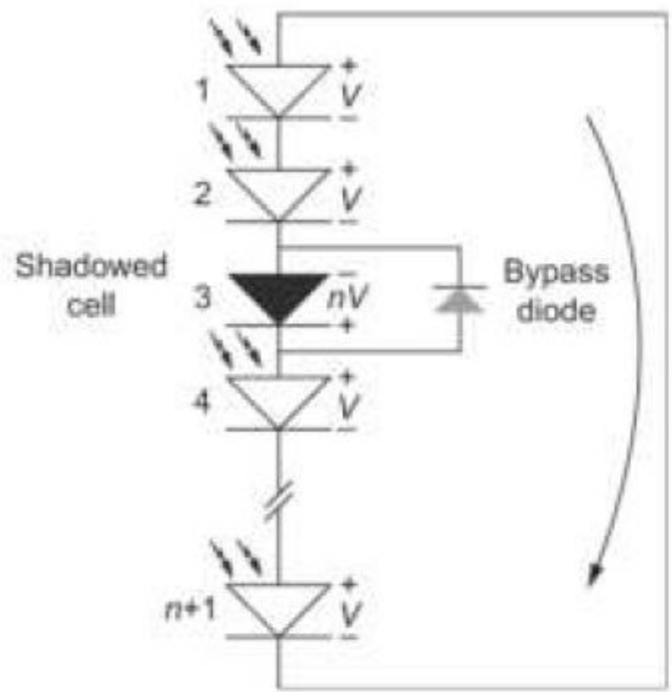


Fig. 6.19 Shadowed cell and bypass diode connection

Solar PV Panel:

- Multiple solar modules connected in series / parallel combination to extract large voltage and current and thus increase the output power.

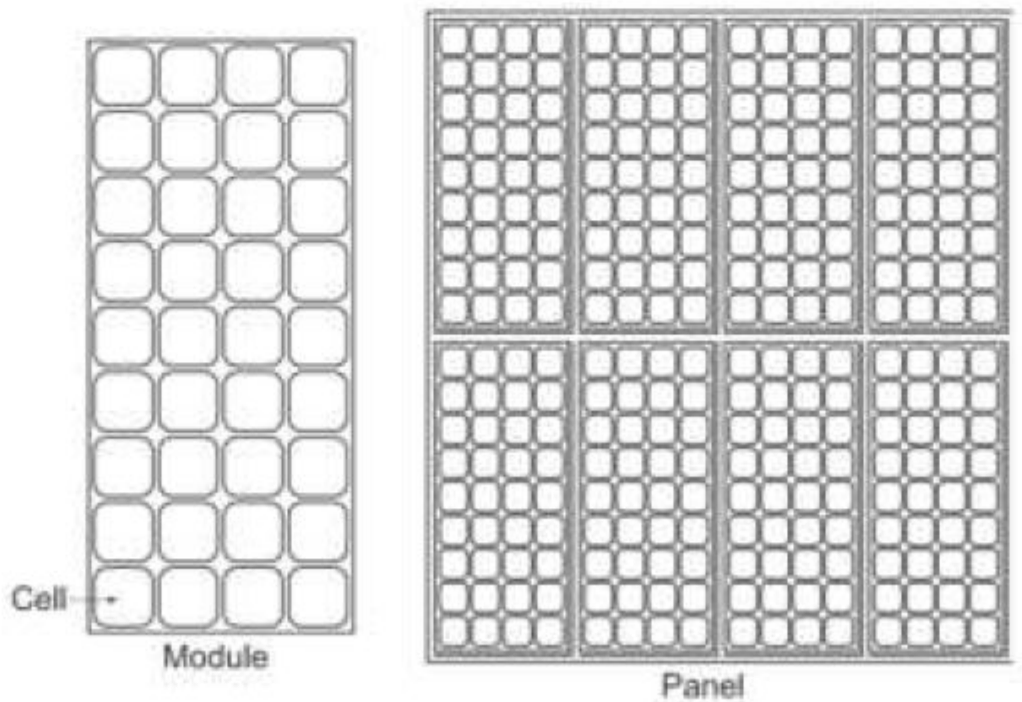
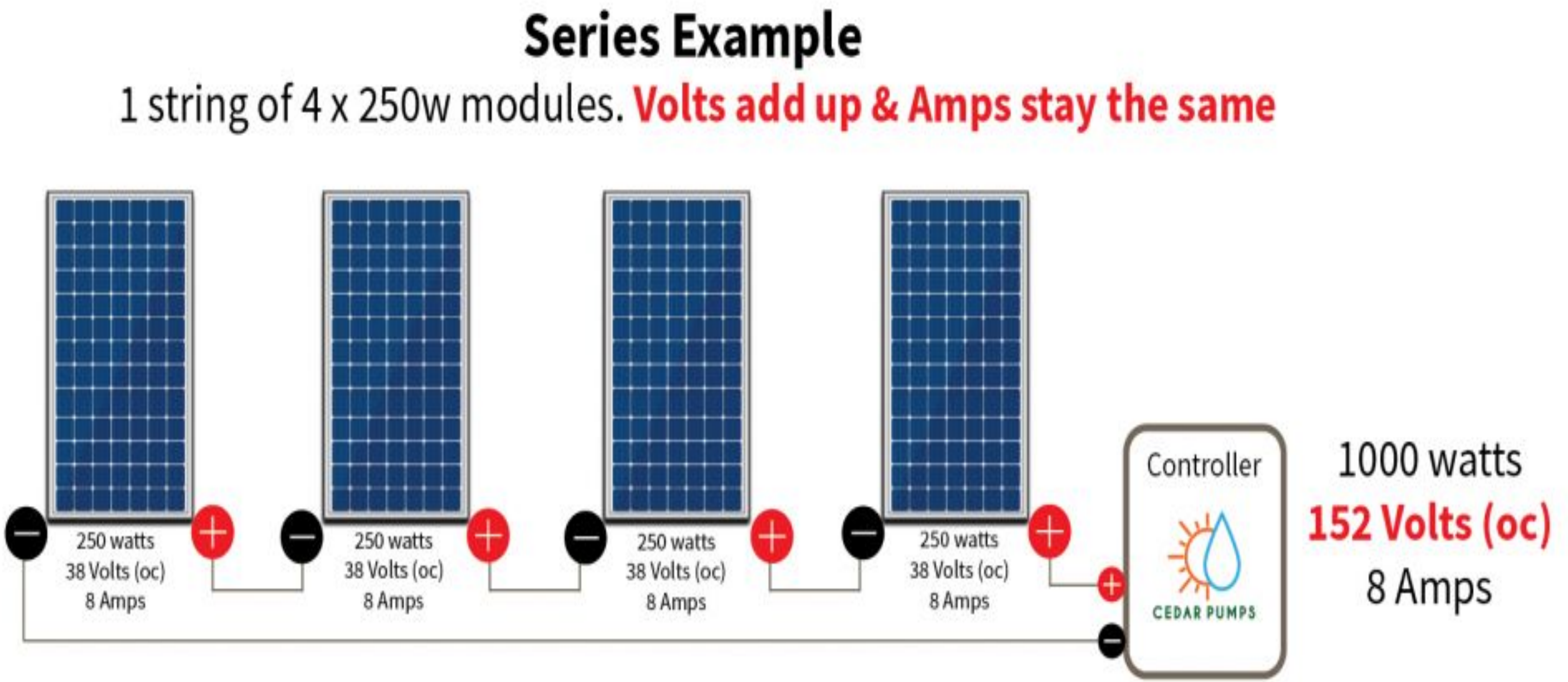


Fig. 6.20 *Cell, module and panel*

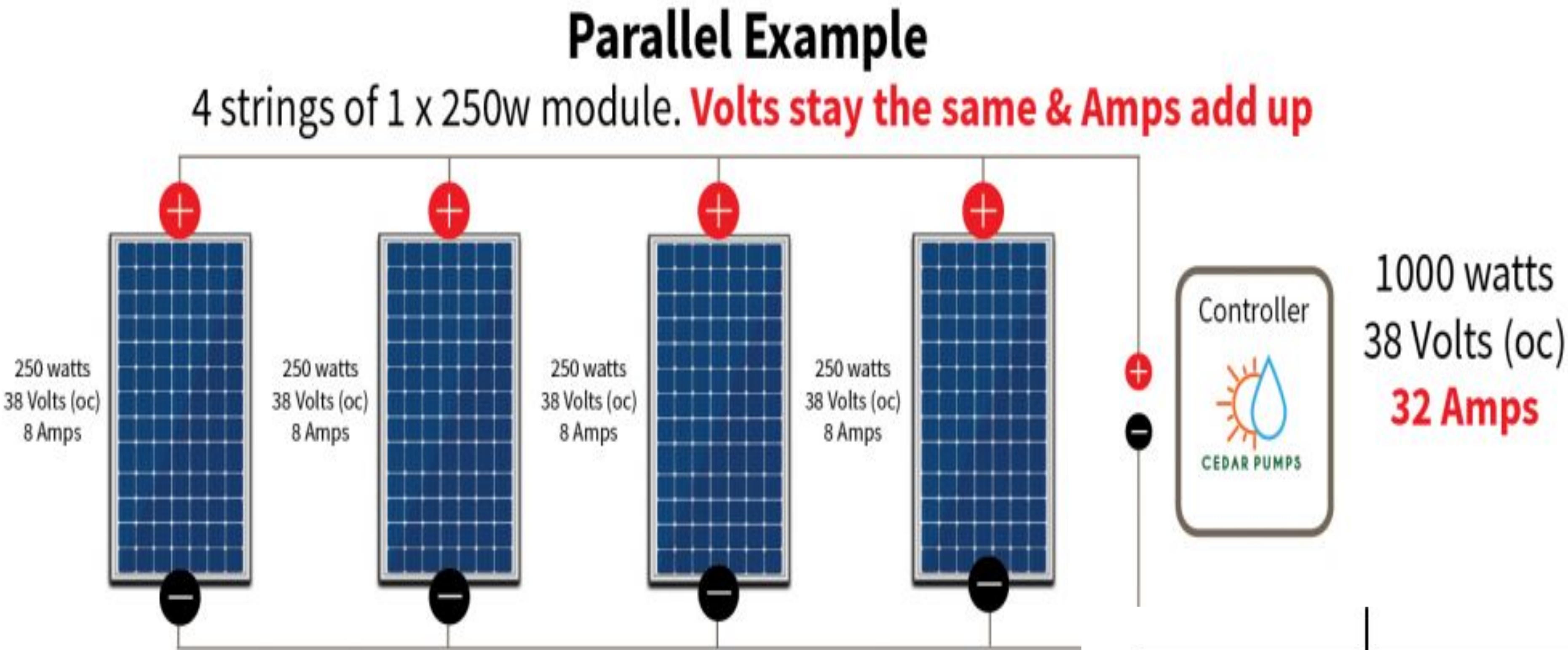
Modules connected in series:

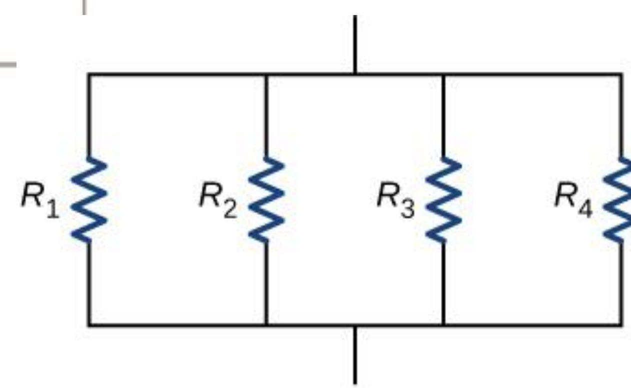
- Voltage gets added and current remains same.
- Power= Voltage * Current



Modules connected in series:

- Voltage remains same where as current gets added.

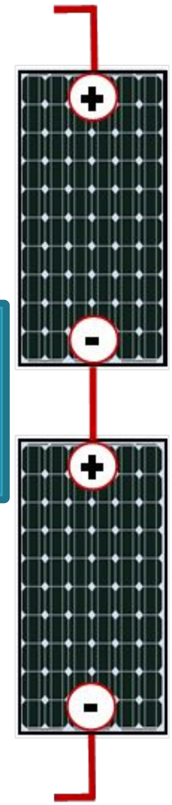


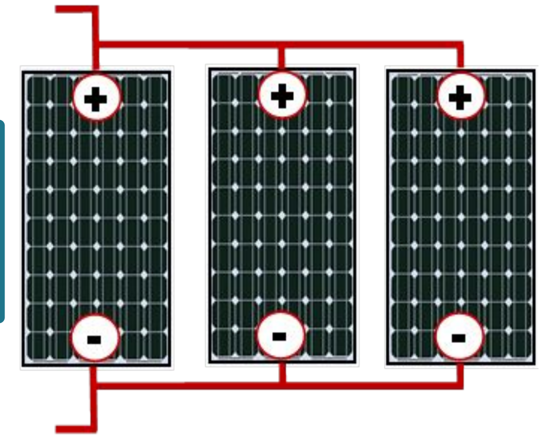


Each Module

12 Volts

5 Amps





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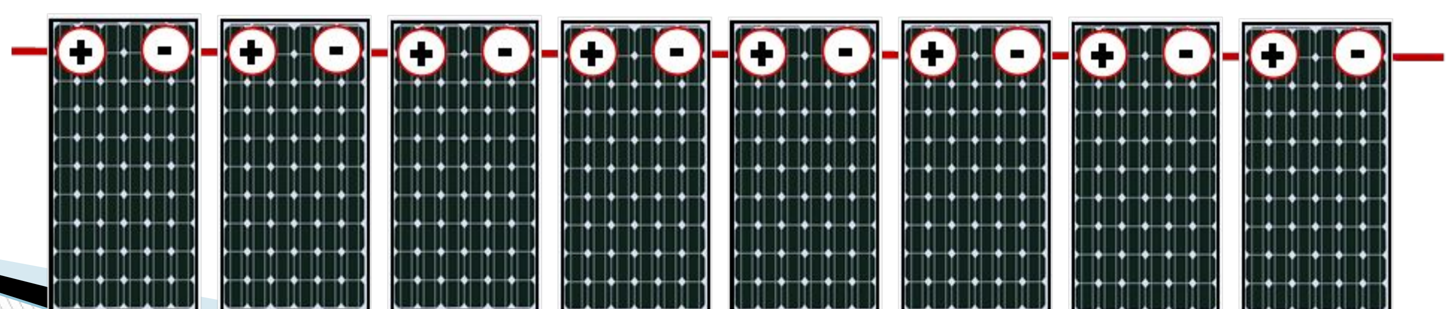


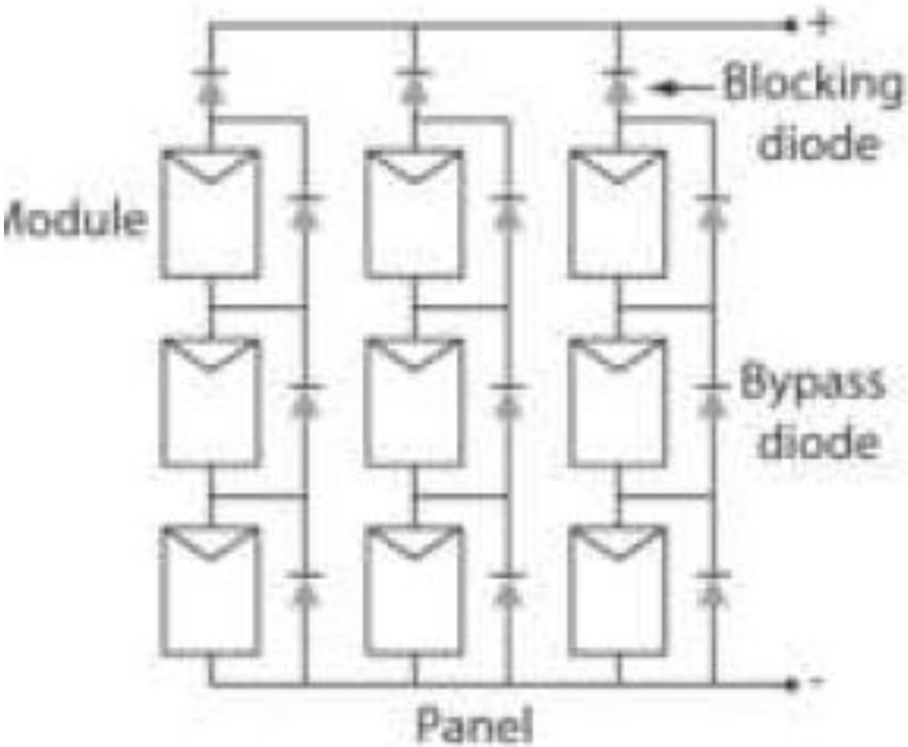
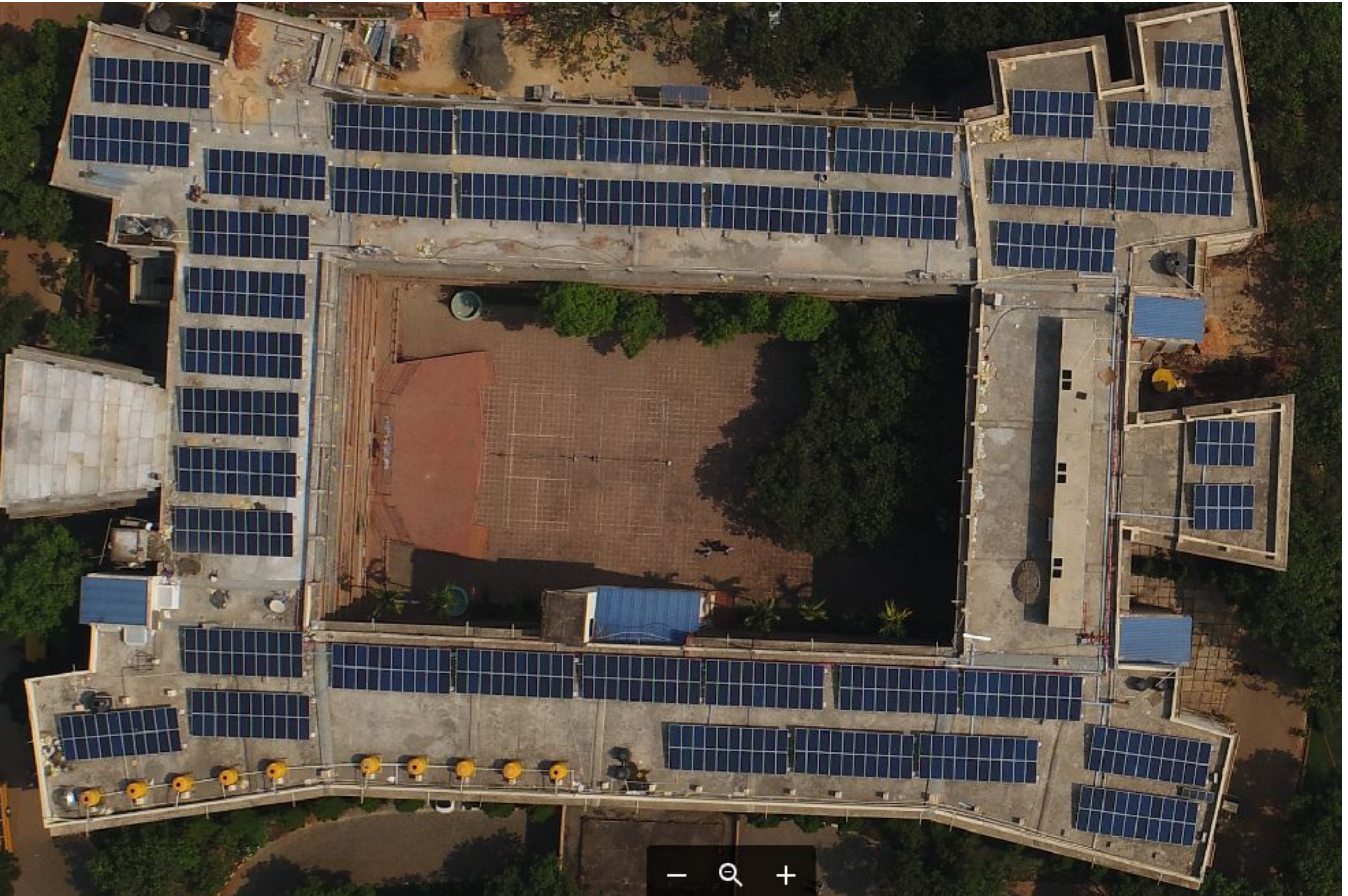


Fig. 6.21 *A typical panet series-parallel connection of modules*

- Blocking diode blocks the flowing of power in that string incase any fault occurs in a particular module.
- Bypass diode will bypass the panel incase any fault ocures in that panel.

Solar PV Array:

- Interconnection of multiple solar panels is called solar Array.
- These arrays are mounted on a structure with an appropriate tilt angle with or without tracking system such that its shadow does not falls on other panels during any time of a days throughout the year.



Example 6.3

A PV system feeds a dc motor to produce 1 hp power at the shaft. The motor efficiency is 85%. Each module has 36 multicrystalline silicon solar cells arranged in a 9 × 4 matrix. The cell size is 125 mm × 125 mm and the cell efficiency is 12%. Calculate the number of modules required in the PC array. Assume global radiation incident normally to the panel as 1 kW / m².

Solution

Motor output power = 1 hp = 735 W

Electrical power required by the motor = 735 / 0.85 = 864.7 W

Cell area in one module = $9 \times 4 \times 125 \times 125 \times 10^{-6} = 0.5625\ \text{m}^2$

Let N number of modules be required.

Solar radiation incident on panel = $1\ \text{kW/m}^2 = 1000\ \text{kW/m}^2$

Cell efficiency = 0.12

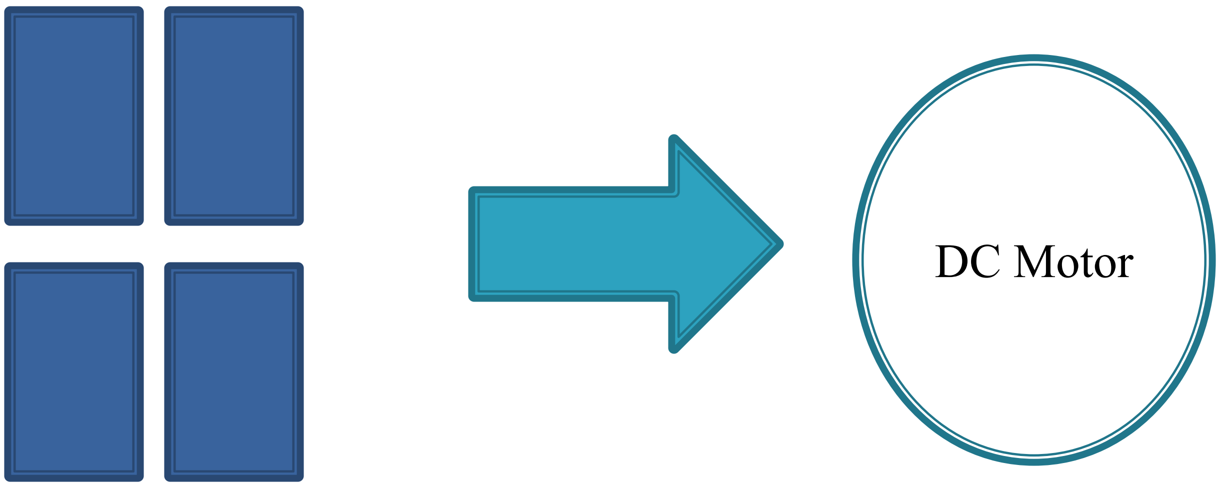
Output of solar array = $1000 \times 0.5625 \times N \times 0.12 = 67.5 \times N$

The output of solar array is the input to the motor;

$$67.5 \times N = 864.7$$

$N = 12.8 \approx 13$

Therefore, 13 modules are required in the panel.



A PV system feeds a dc motor to produce 5 hp power at the shaft. The motor efficiency is 85%. Each module has 36 multicrystalline silicon solar cells arranged in a 9 × 4 matrix. The cell size is 125 mm × 125 mm and the cell efficiency is 12%. Calculate the number of modules required in the PC array. Assume global radiation incident normally to the panel as 1 kW / m².

❑Stand-alone and grid connected

- ***Stand-alone Solar PV System:***

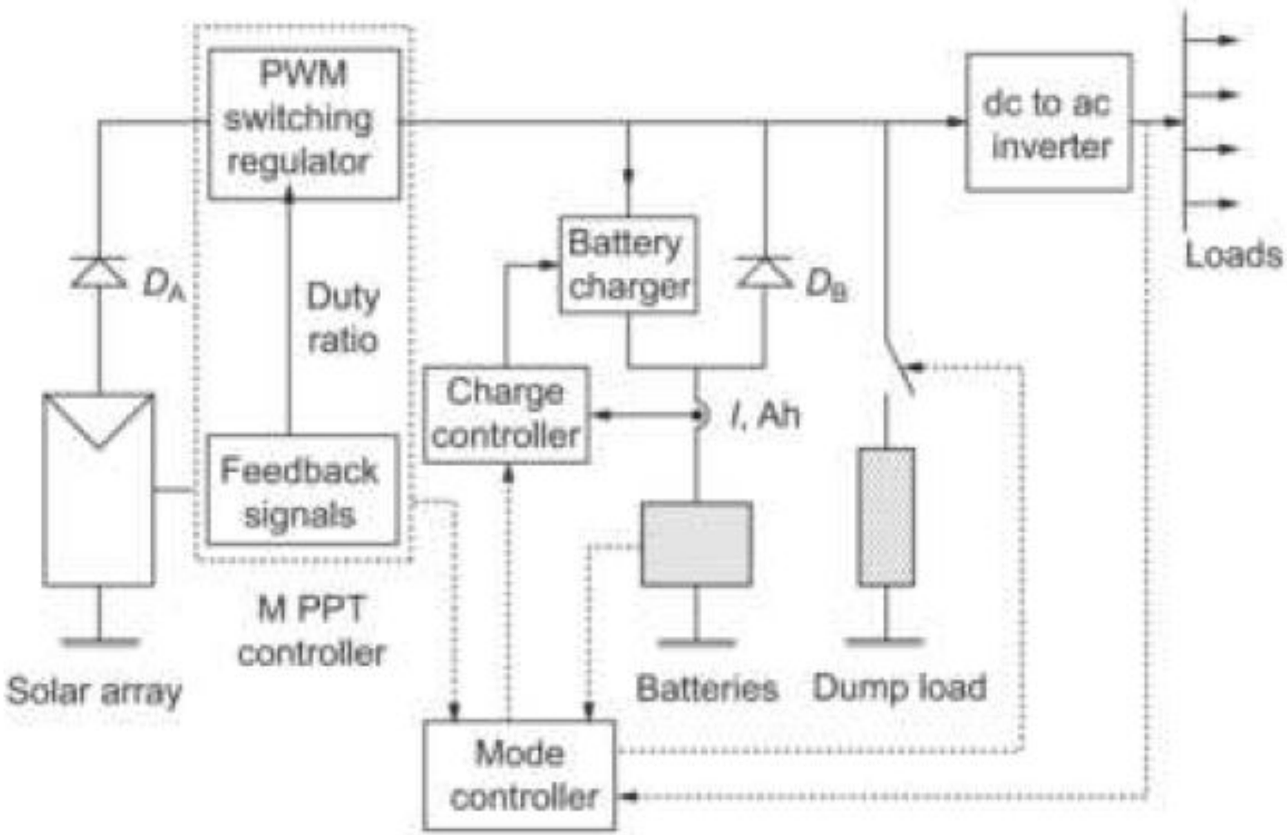


Fig. 6.26 *A general stand-alone solar PV system*

D_A=Battery Discharge Diode avoids the battery to get overcharged.

D_B =Array diode prevents the battery to discharge through PV array

Grid connected Solar PV System

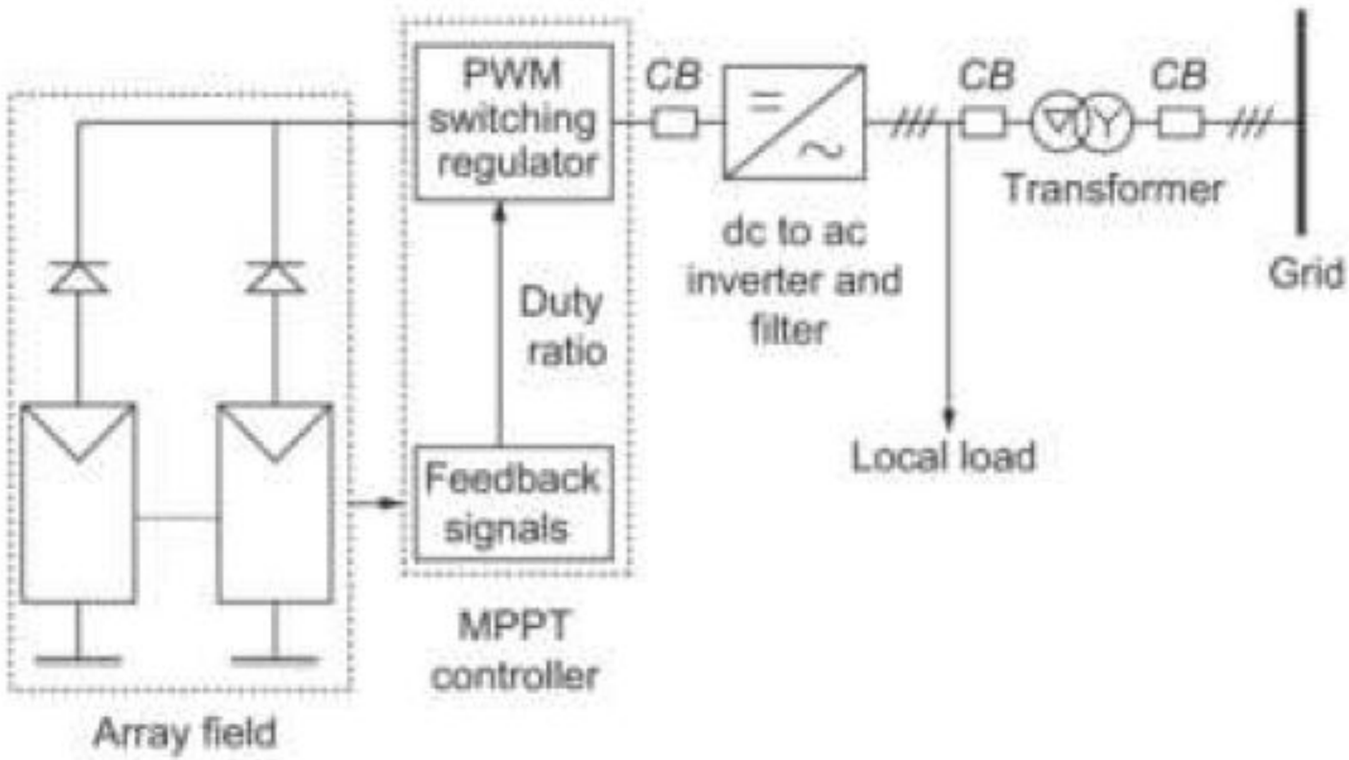
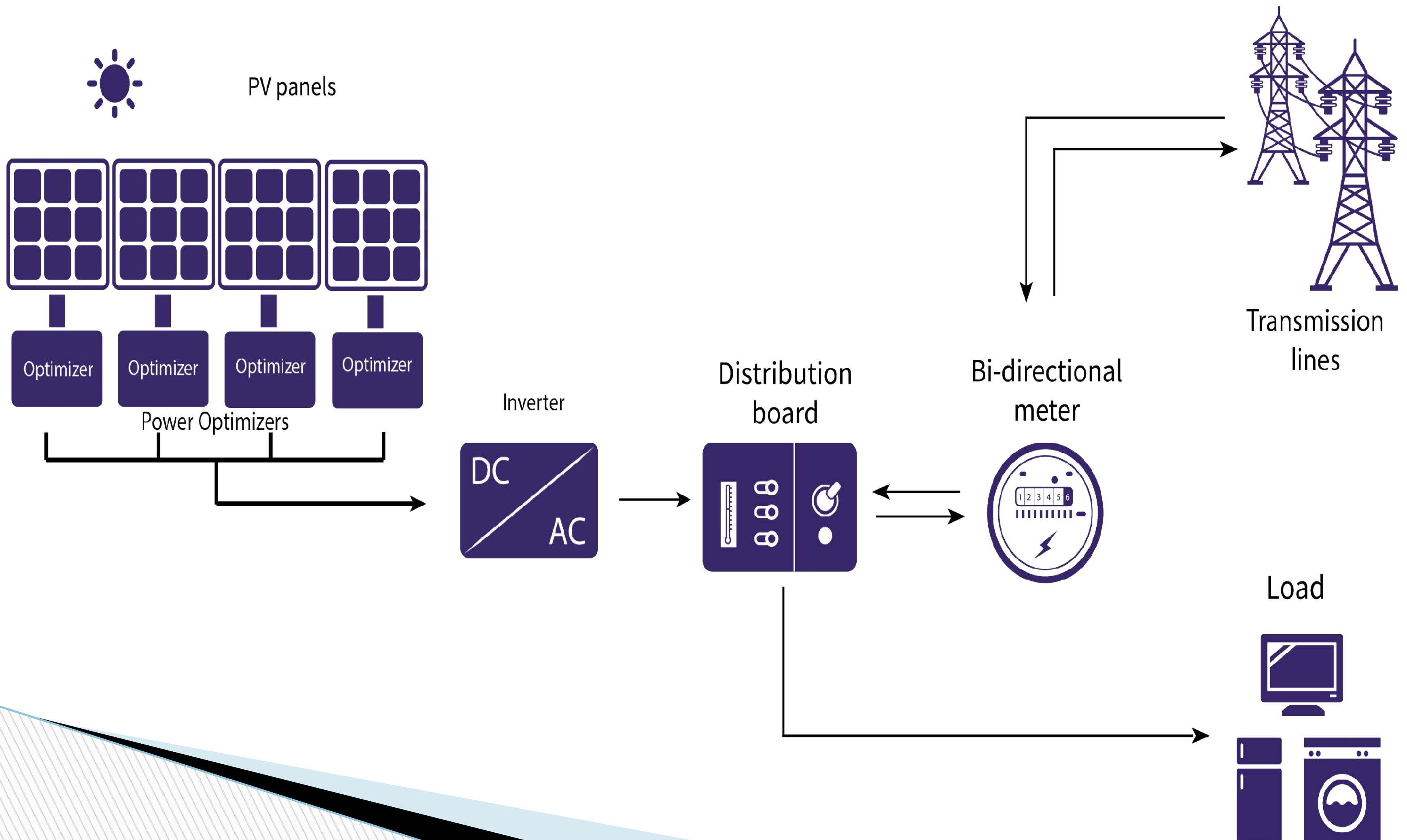


Fig. 6.27 *A general grid-interactive solar PV system*

Connection Diagram as per HESCOM norms:



Applications –

- Street lighting,
- domestic lighting
- solar water pumping systems.

1. Solar PV Street lighting:

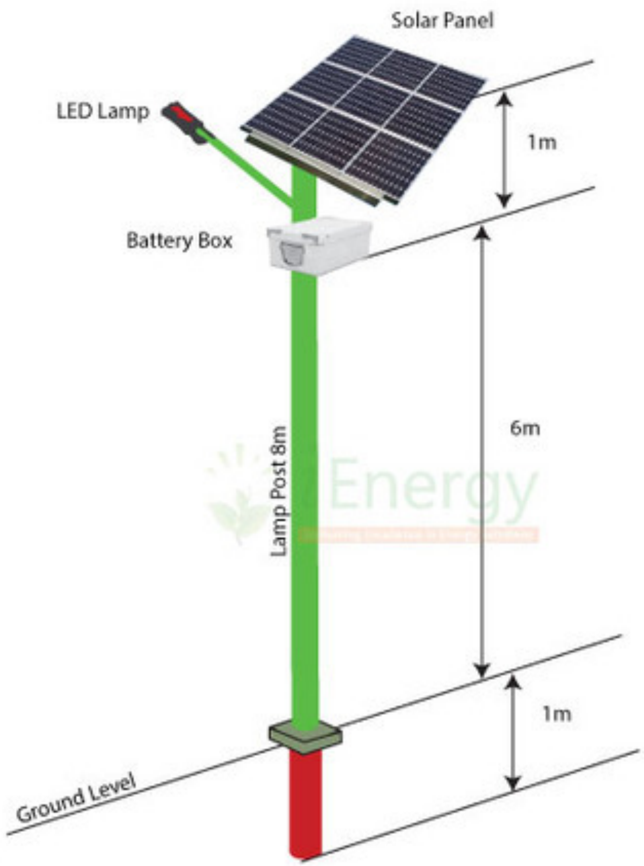
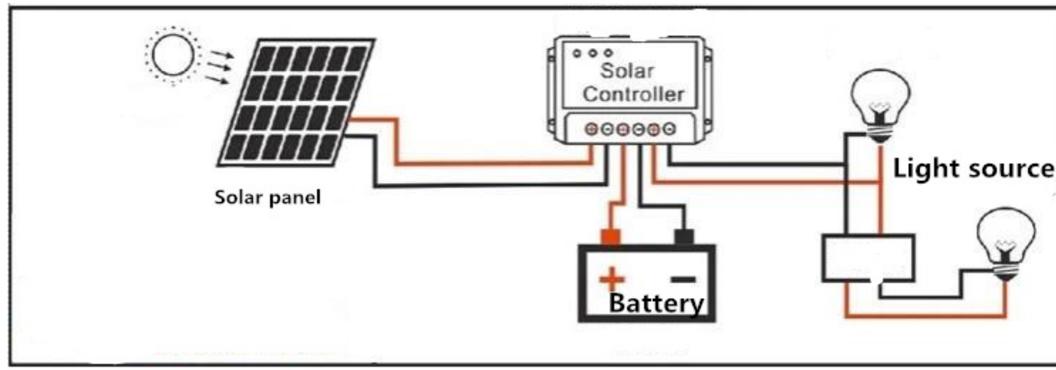


Fig. Solar Street Light Dimensions and Labels



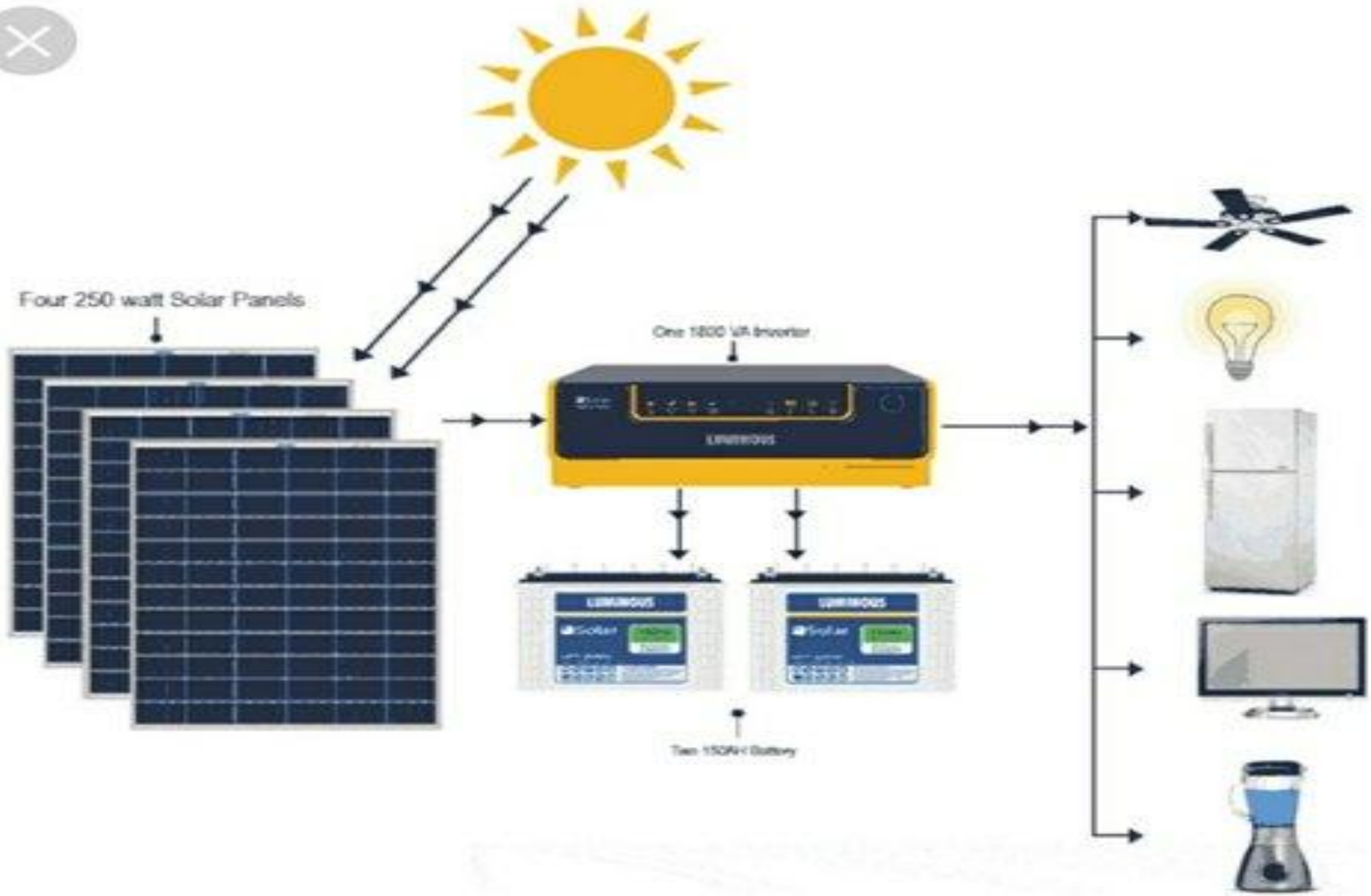
- Variable DC voltage of solar panel is given to the charge controller, where it is converted into a fixed DC voltage and gives it to batteries.
- The charge controller controllers the charging of the battery and disconnects it from the supply when it is fully charged and reconnects it charging lowers.
- The battery discharges when the load is turned ON.



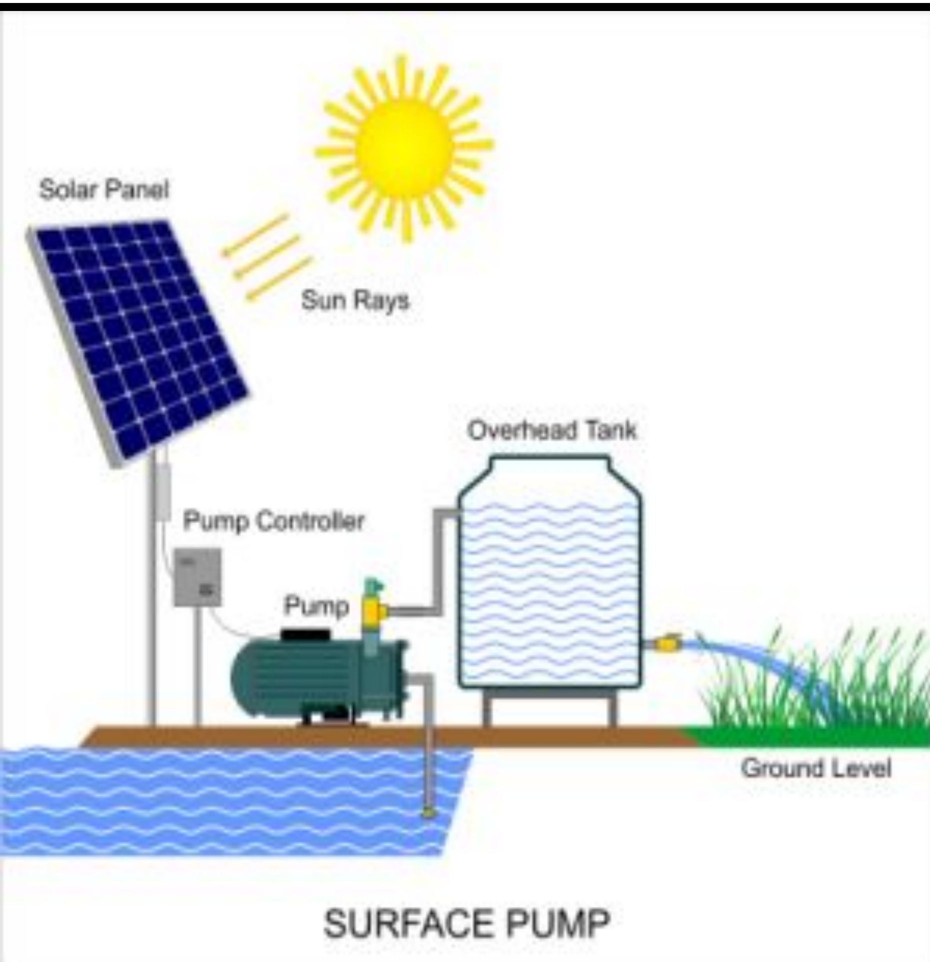
Street Light Design calculation:

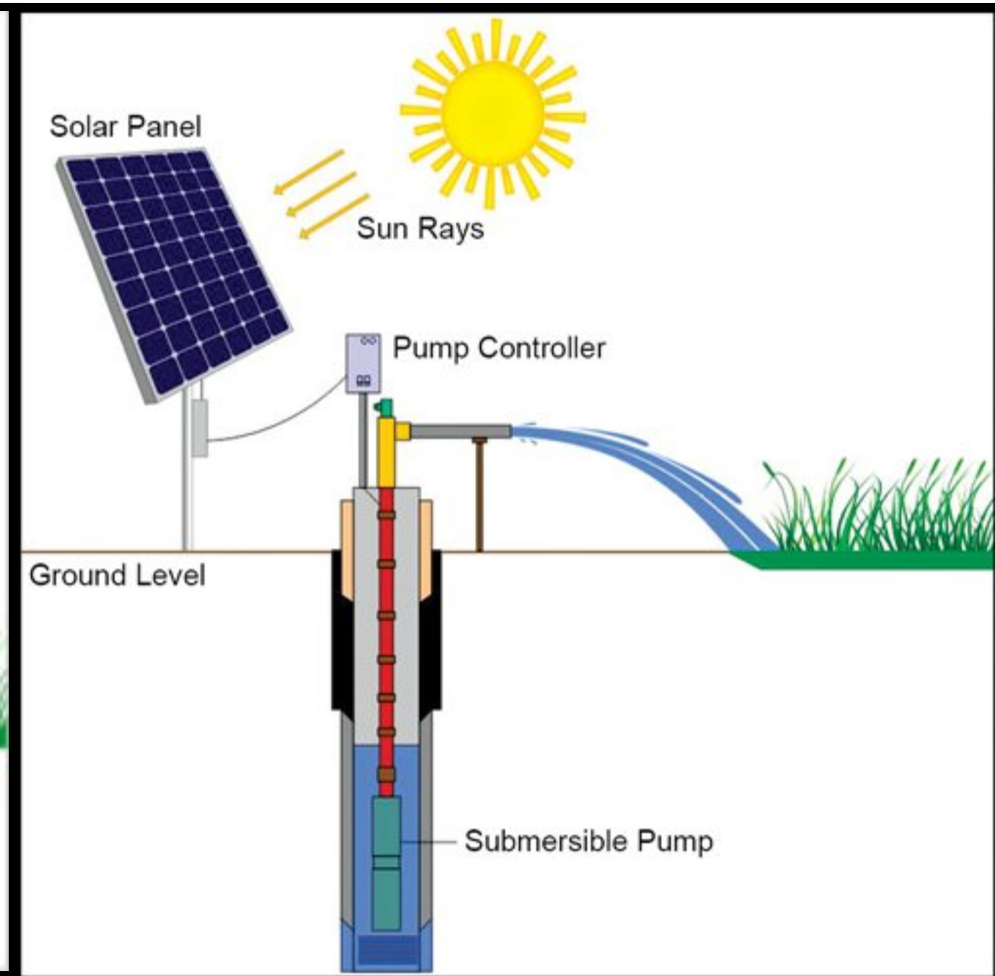
- Assume, LED Street light capacity: 36 W
- Energy consumed per day:
  - Let the street light is on for 11 hrs per day (7pm to 6 am)
  - Energy consumed= power * Time = 36*11= 396 Wh/day
- Charge controller capacity= 36W/ 12V = 3Amps.
  - Thus a charge controller of 3 amp rating can be used.
- Battery calculation:
  - Let the battery used be of 12V.
  - Ampere hour required= 396 Wh per day / 12V =33 Amp-Hour
  - But the depth of Discharge of a battery is 70%.
  - So, 33*1.3= 42.9 Ah battery is required.
- PV Panel sizing:
  - On an average 1kW PV panel can generate 4 kWh per day
  - PV panel capacity=396/4 =99.9 W=100W.

2. domestic lighting



3. Solar water pumping system:





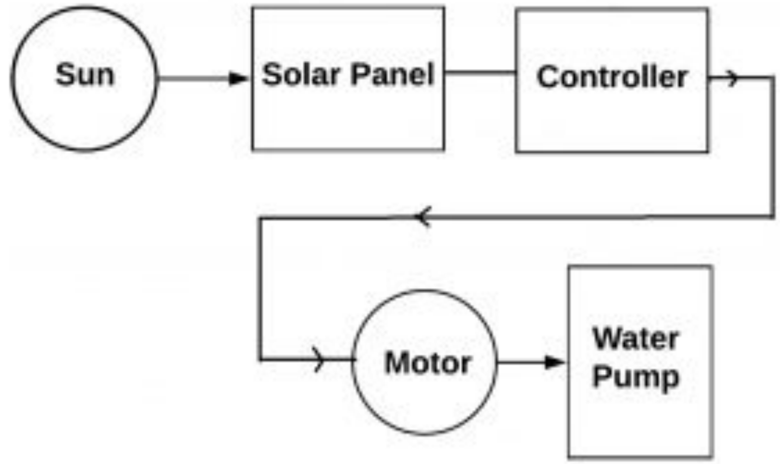


Fig: Block diagram of solar water pumping system

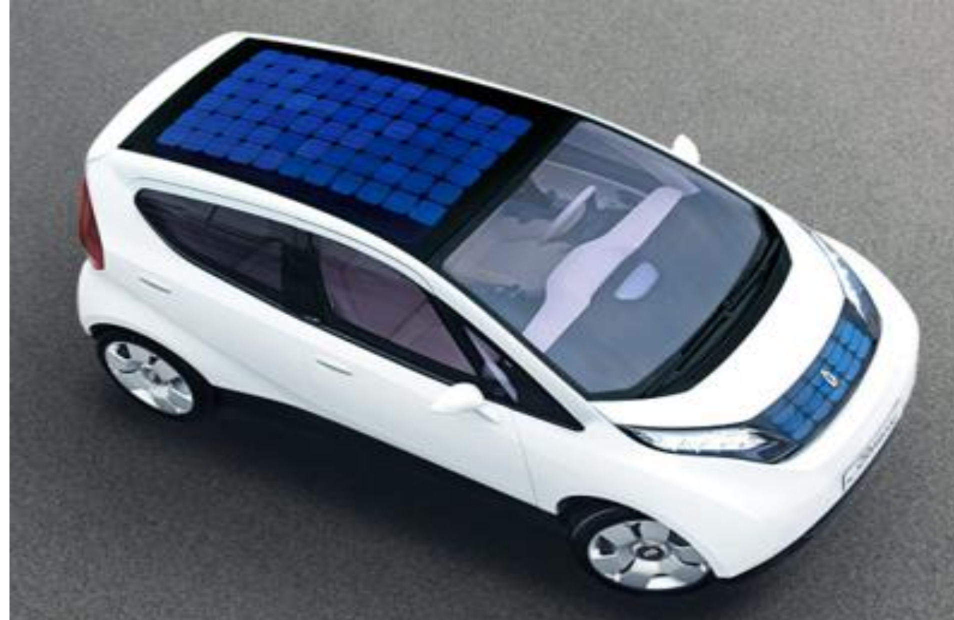
Pumping of water for the purpose of drinking or for minor irrigation during sunshine hours is a very successful application of a standalone PV system without storage. Water pumping appears to be most suited for solar PV applications as water demand increases during dry days when plenty of sunshine is available. There would be less need of water during the rainy season when the availability of solar energy is also low. SPV water-pumping systems have been successfully used in many parts of the world in the range of few hundred W_p to 5 kW_p. An SPV water-pumping system is expected to deliver a minimum of 15,000 litres per day for a 200-W_p panel and 1,70,000 litres per day for 2,250 W_p panel from a suction of 7 metres and/or a total head of 10 metres on a clear sunny day. Three types of motors have generally been used: (i) permanent magnet dc motor, (in low-capacity pumping systems), (ii) brushless dc motors, and (iii) variable voltage and variable frequency ac motors, with appropriate electronic control and conversion system.

Other applications: (Not in syllabus)

solar refrigerator

Solar Ship:

Solar Car:



Solar parking:

Floating Solar:


Telecommunication
Offshore Oil Drilling
PV Refrigerator
Power Pack (Army Tent)
Solar Lentern
Domestic lighting System
Battery Charging Station
PV Integrated Building
PV Pump
Railway Signaling

Thank You